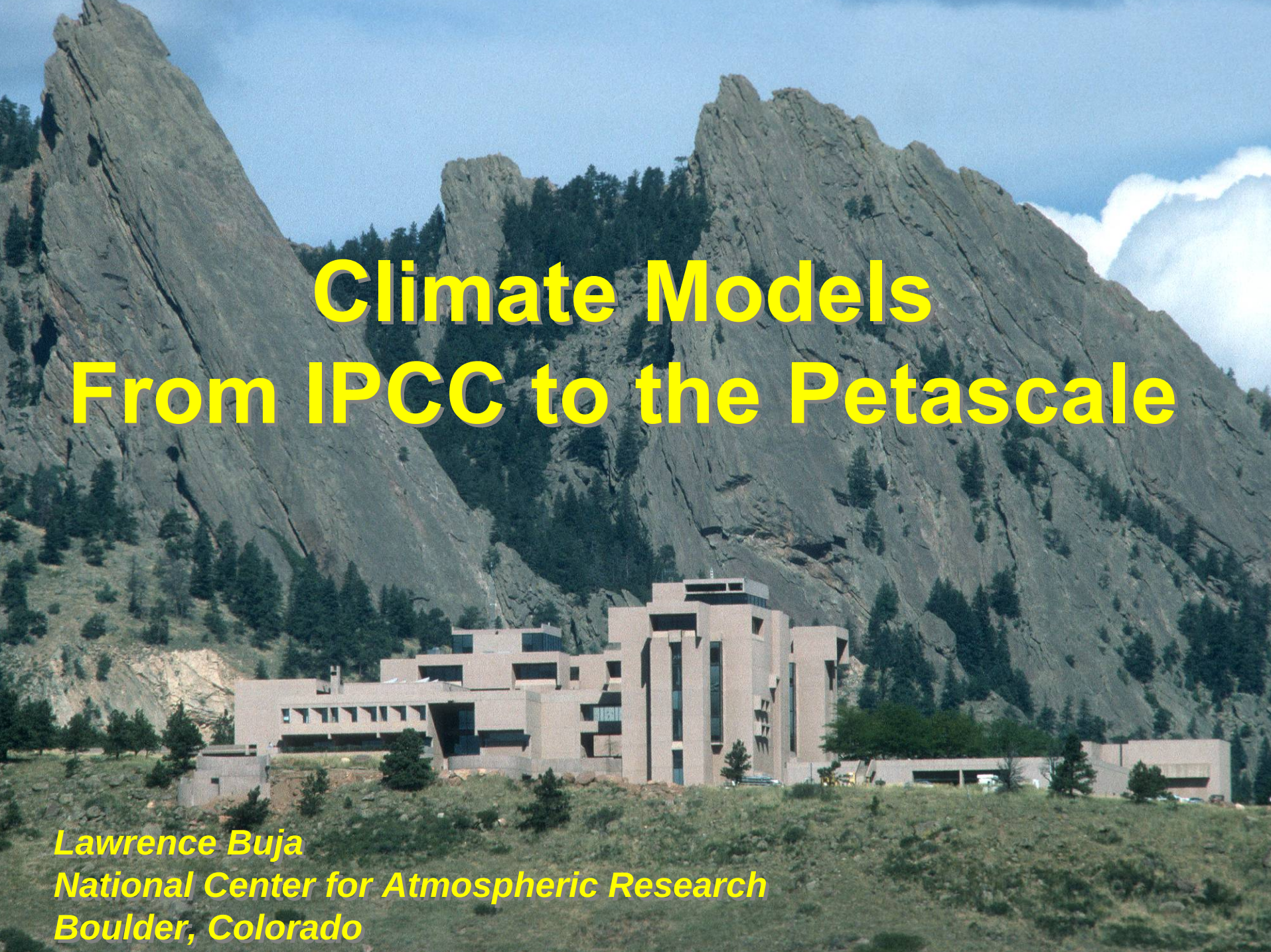
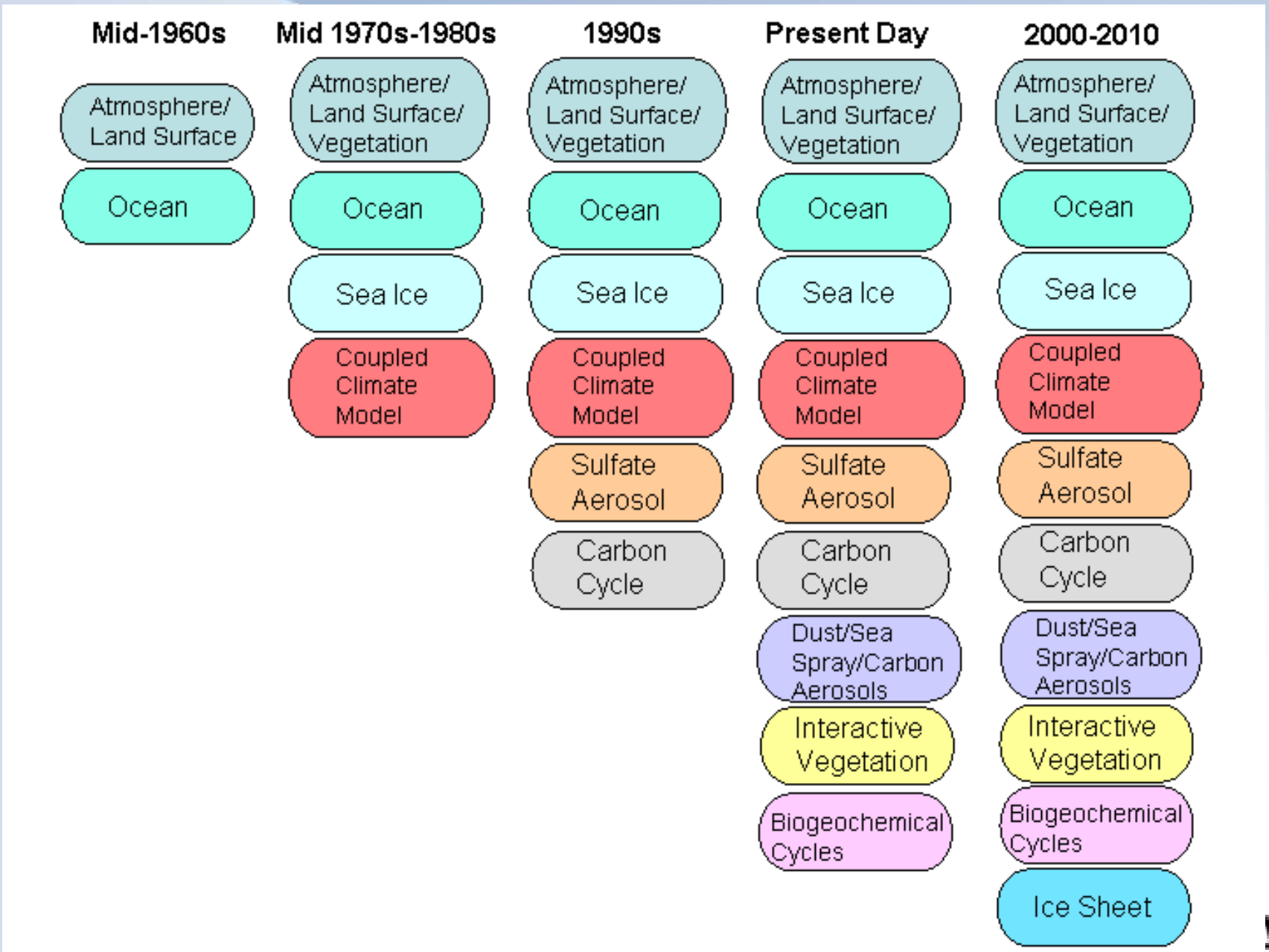


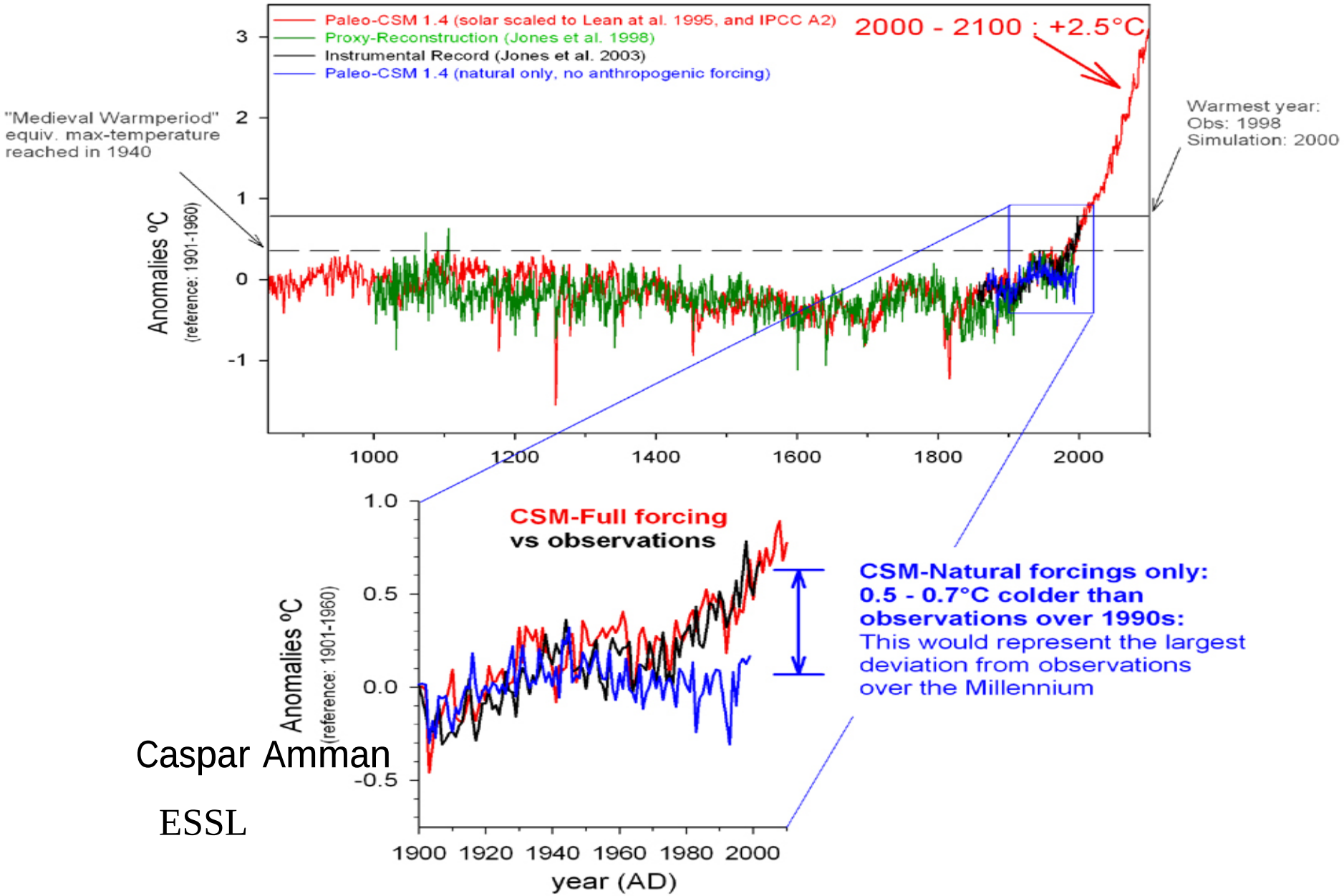
Climate Models
From IPCC to the Petascale

Lawrence Buja
National Center for Atmospheric Research
Boulder, Colorado

Timeline of Climate Model Development

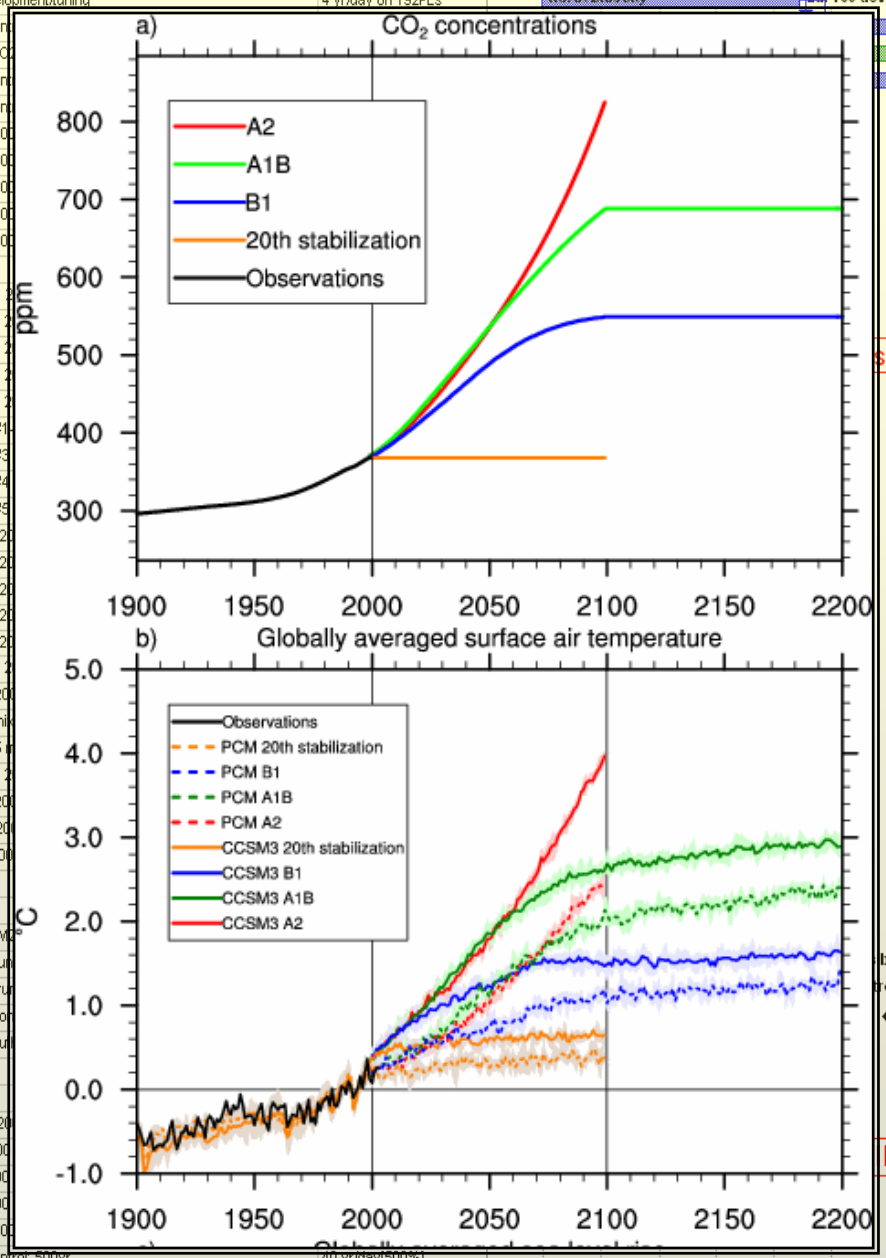


Climate of the last Millennium



Caspar Amman

ESSL



IPCC AR4

Internationally coordinated

Climate benchmark suite

4 Future Scenarios

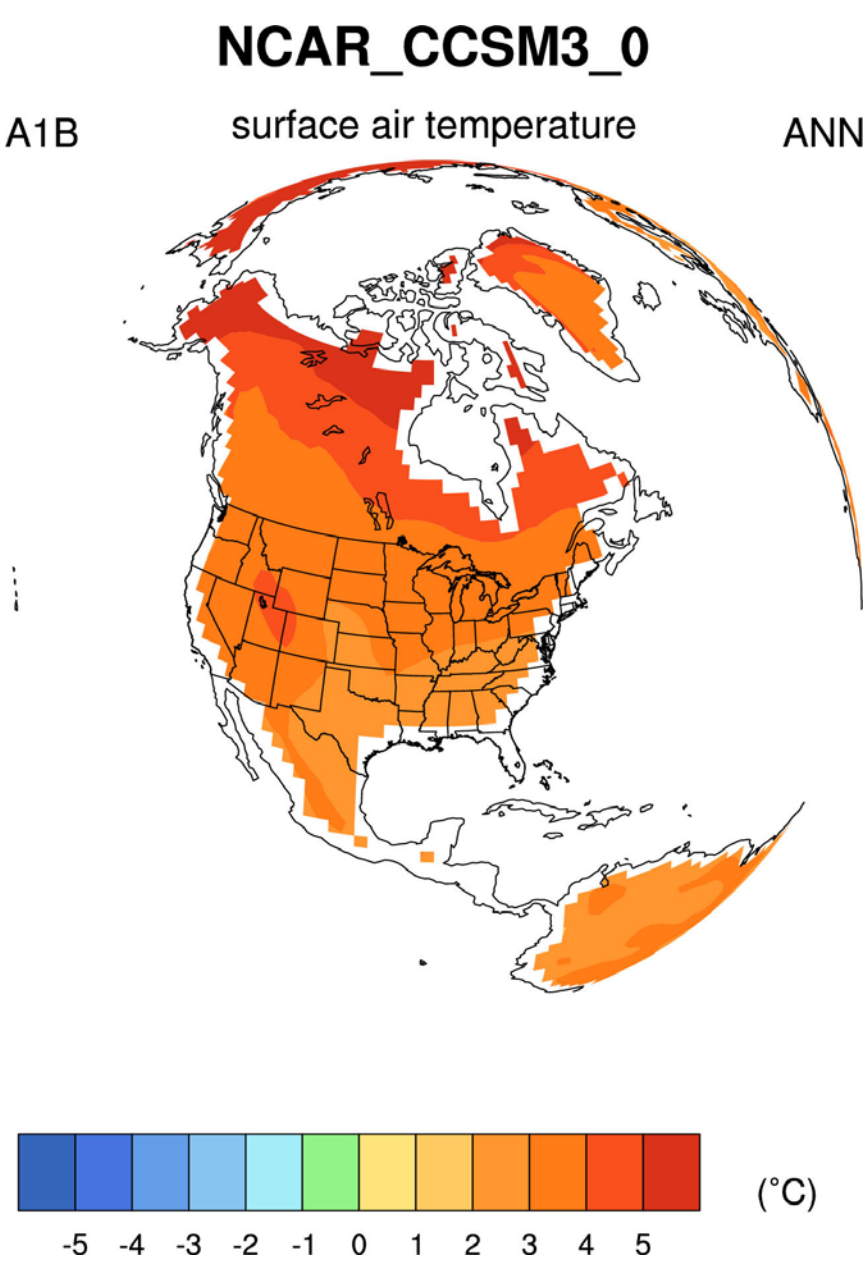
2003 Model development

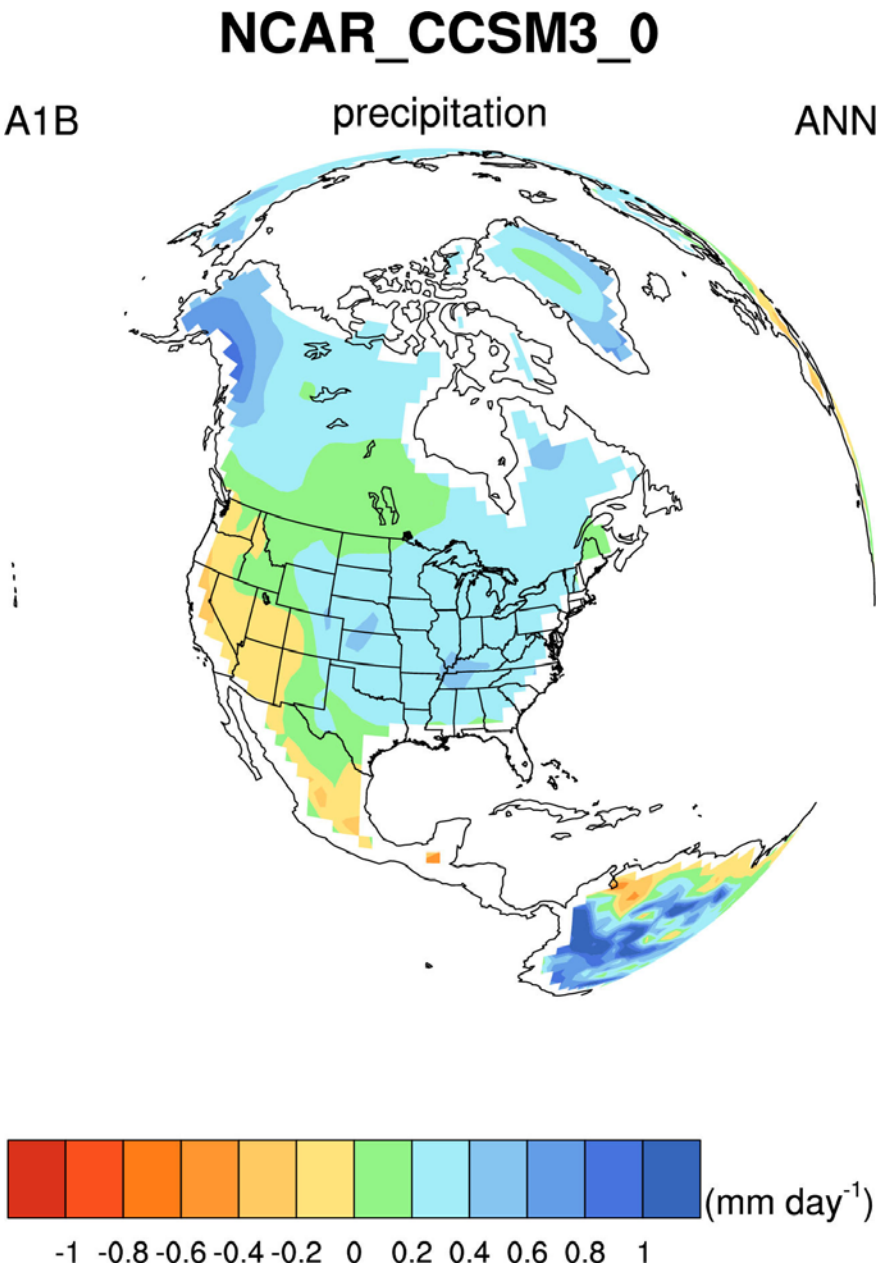
2004 Simulations

2005 Data PP & Analysis

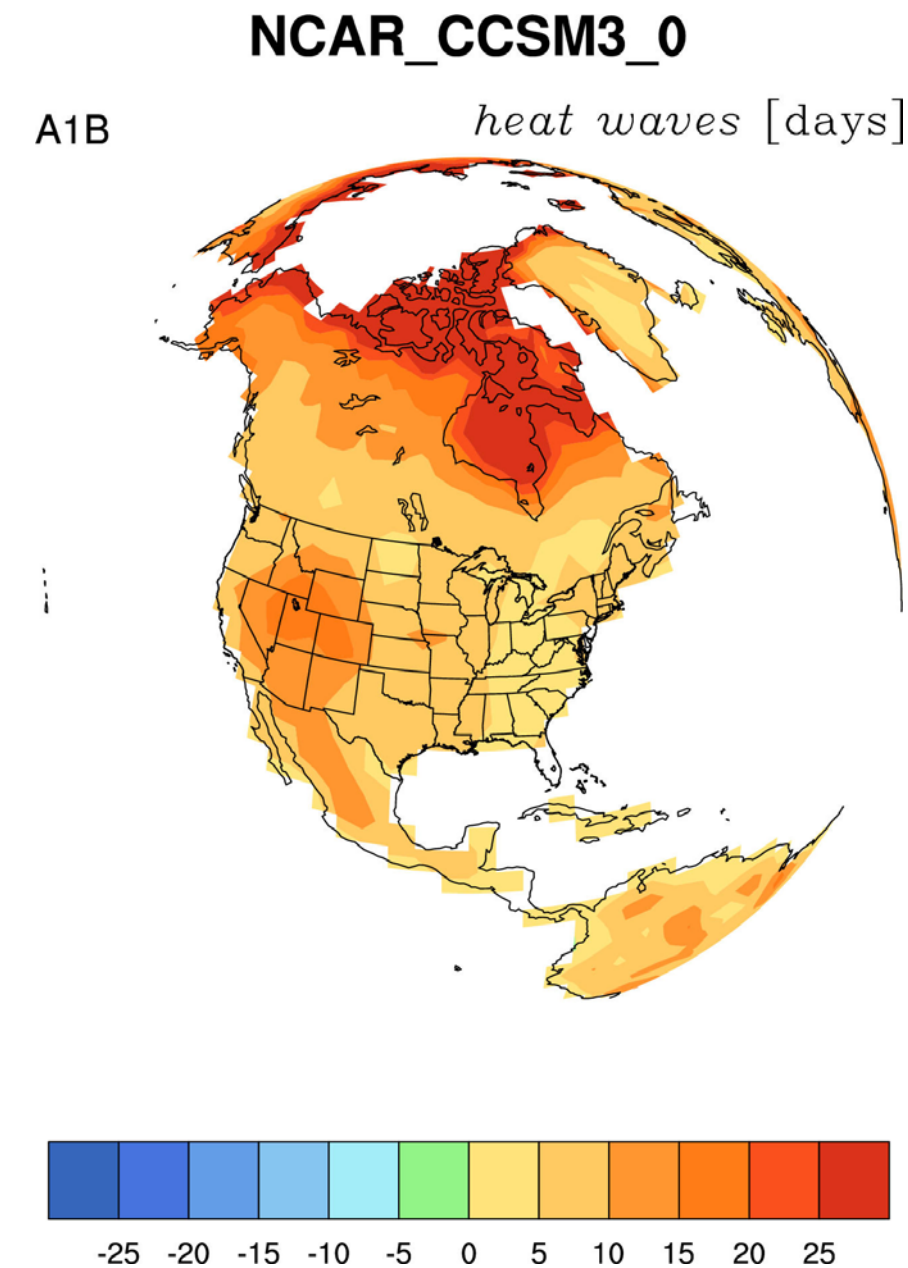
2006 Scientific Input

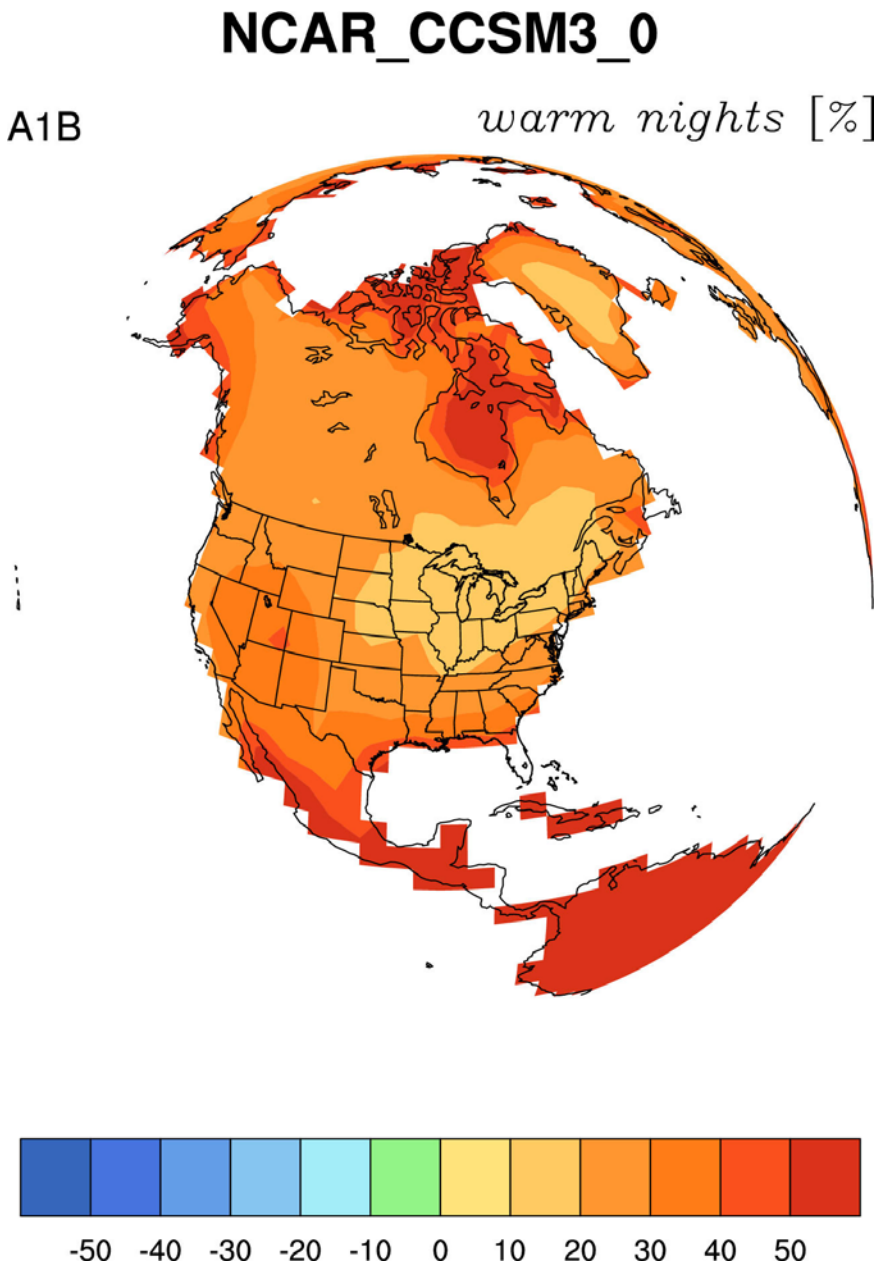
2007 Publication



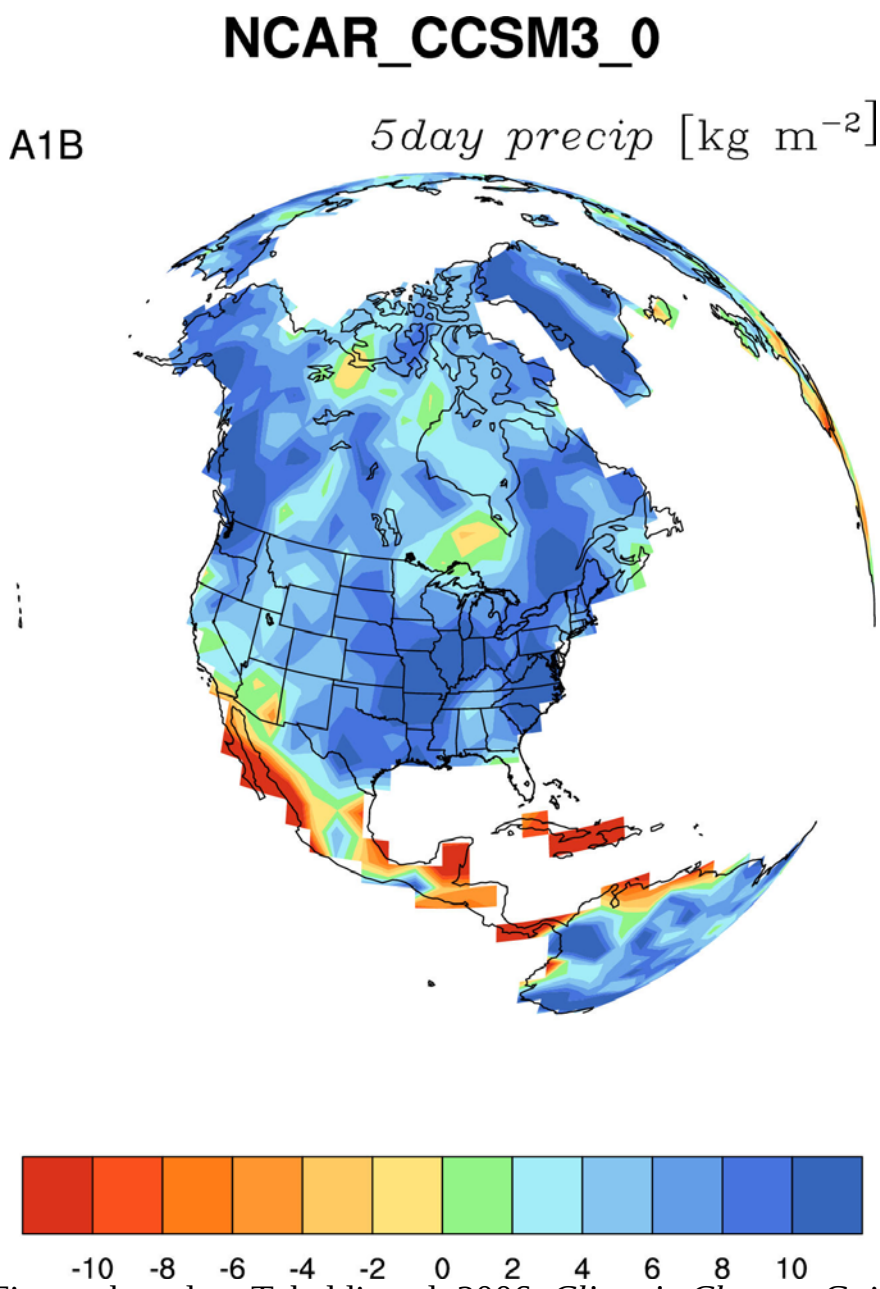


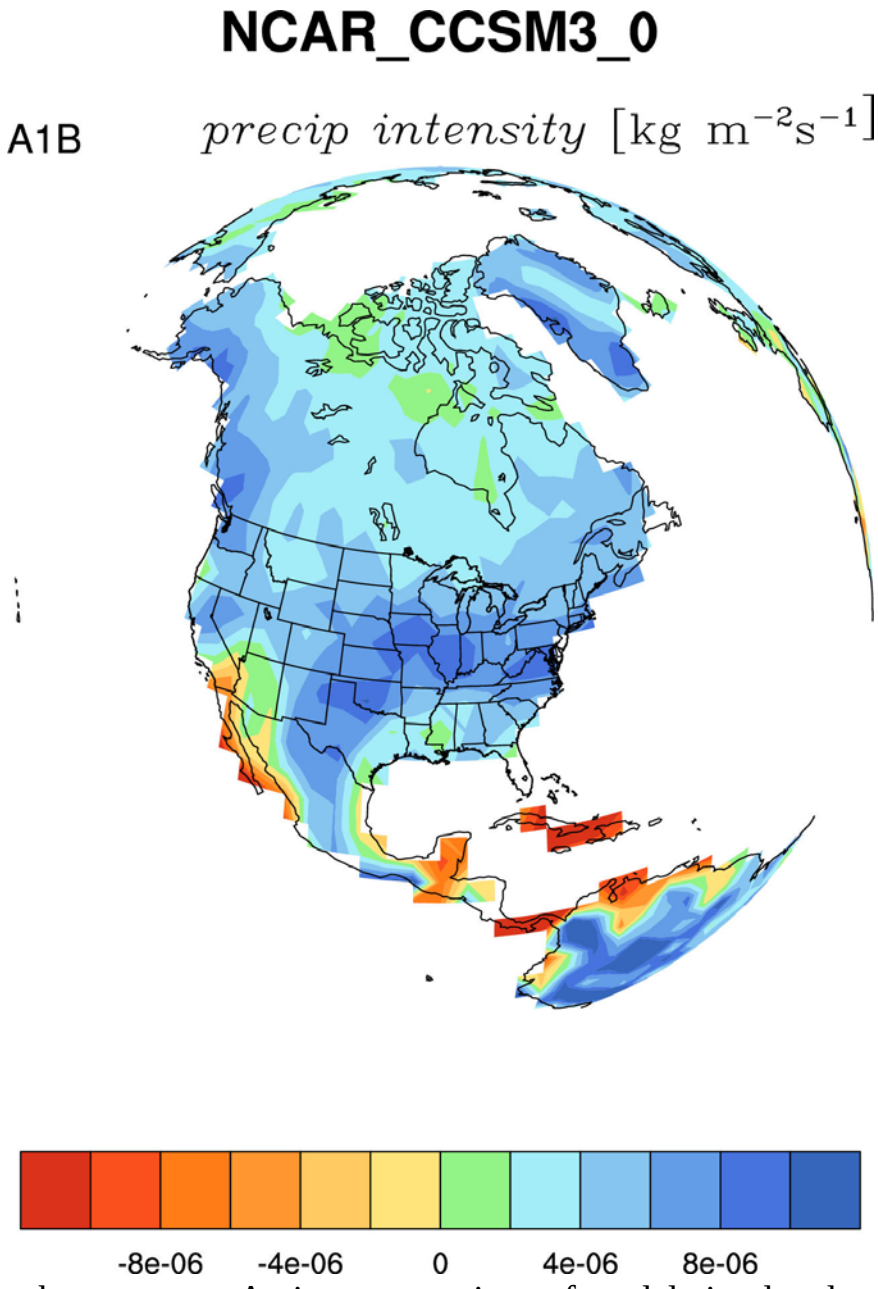
Figures based on Tebaldi et al. 2006: *Climatic Change,* Going to the extremes; An intercomparison of model-simulated historical and future changes in extreme events, http://www.cgd.ucar.edu/ccr/publications/tebaldi-extremes.html



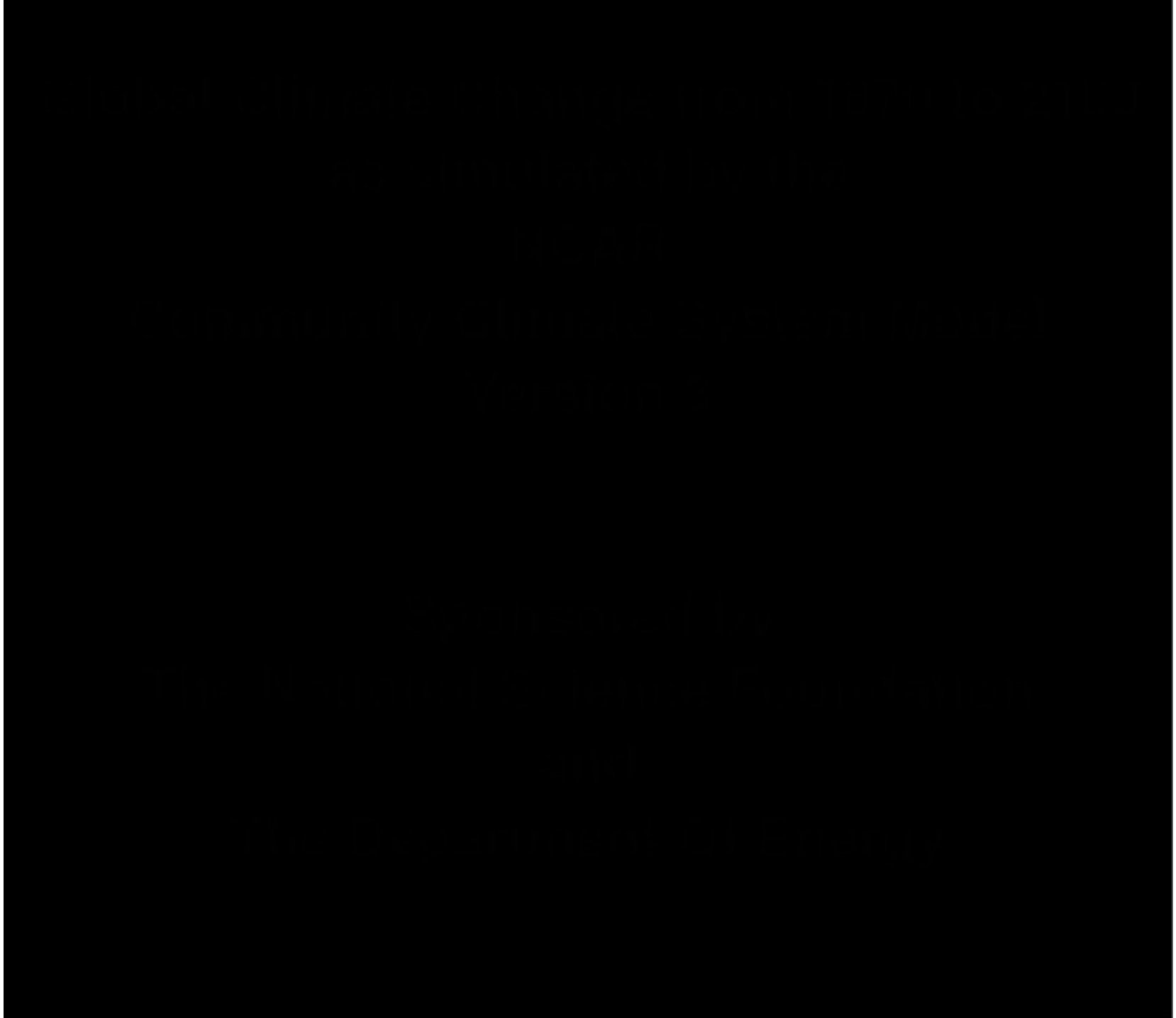


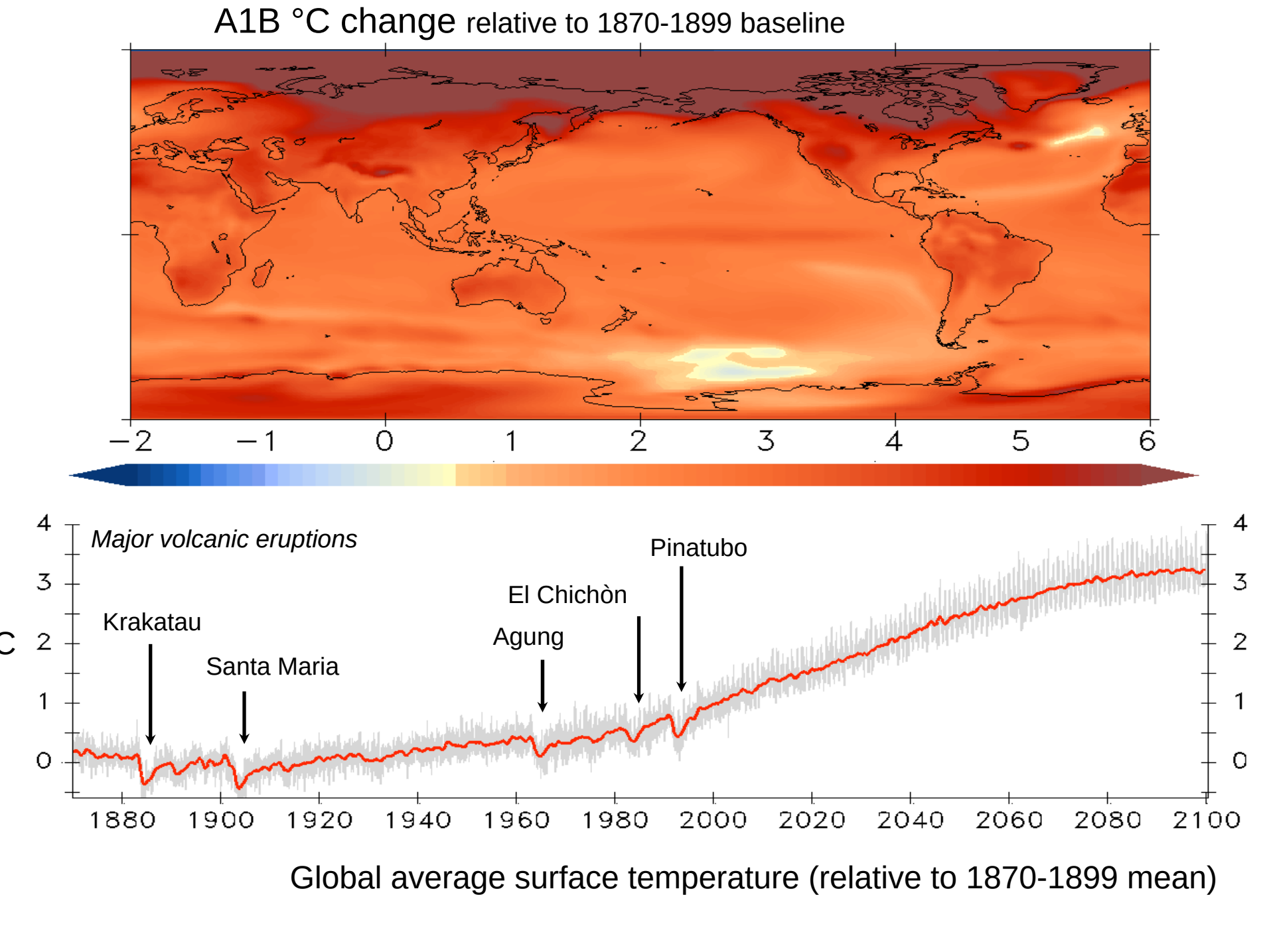
Figures based on Tebaldi et al. 2006: *Climatic Change*, Going to the extremes; An intercomparison of model-simulated historical and future changes in extreme events, http://www.cgd.ucar.edu/ccr/publications/tebaldi-extremes.html





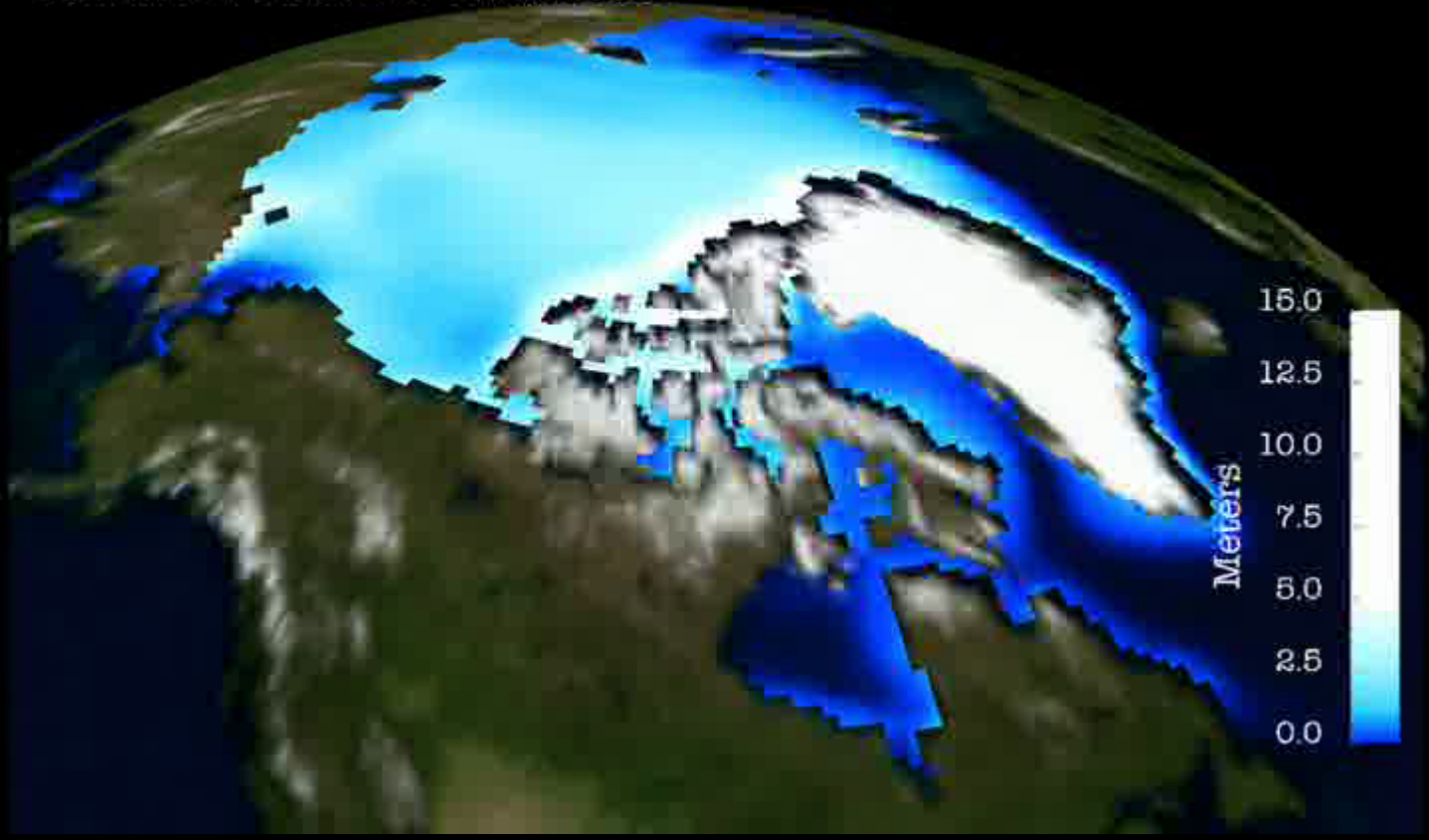
Figures based on Tebaldi et al. 2006: *Climatic Change*, Going to the extremes; An intercomparison of model-simulated historical and future changes in extreme events, http://www.cgd.ucar.edu/ccr/publications/tebaldi-extremes.html




A1B °C change relative to 1870-1899 baseline
−2
−1
0
1
2
3
4
5
6
Major volcanic eruptions
Krakatau
Santa Maria
Agung
El Chichòn
Pinatubo
C
4
3
2
1
0
1880
1900
1920
1940
1960
1980
2000
2020
2040
2060
2080
2100
Global average surface temperature (relative to 1870-1899 mean)

NCAR CCSM3 IPCC A2 Scenario
Summer Sea Ice Thickness

2000

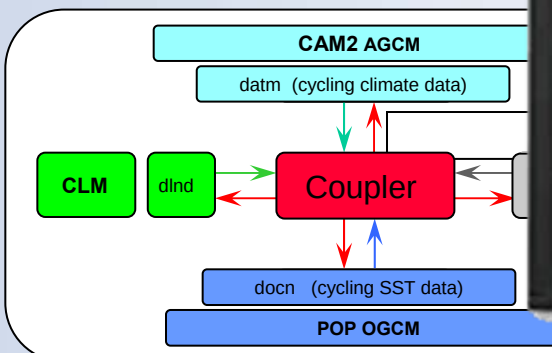


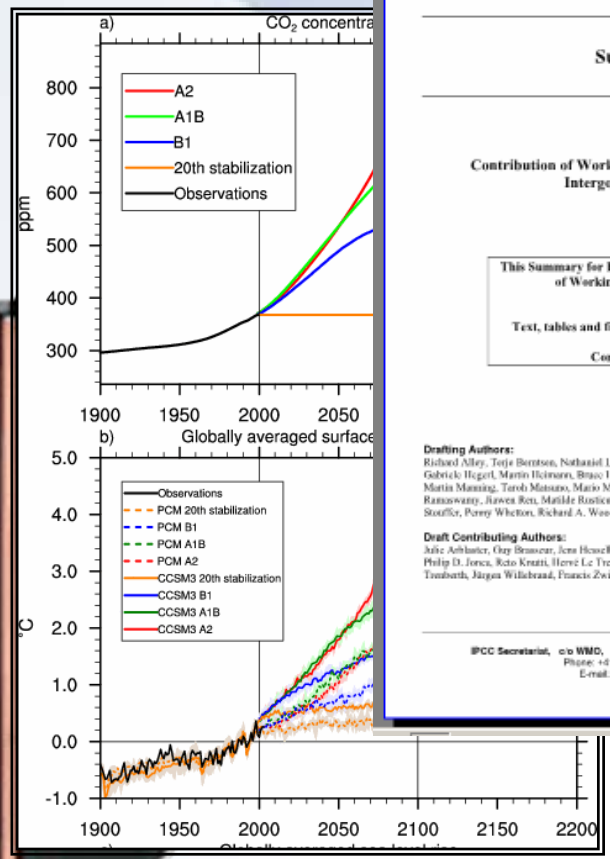
IPCC AR4: Warming is "unequivocal"

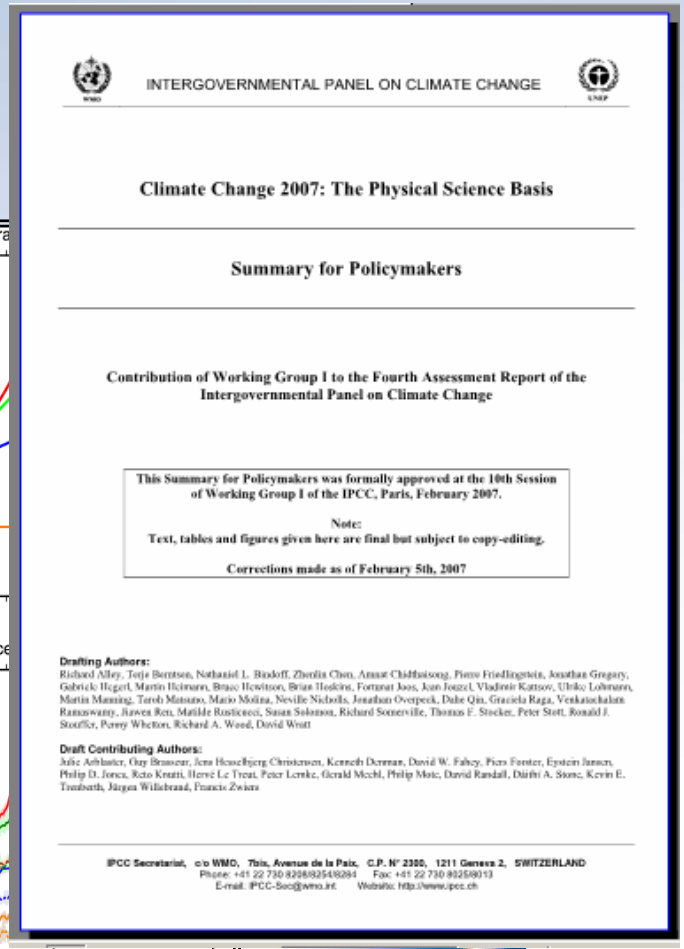
"Very likely" the observed 20th century warming is due to human emissions.

Significant changes in:

- Sea level
- Temperature
- Precipitation
- Snow/Glaciers
- Extremes







INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

Climate Change 2007: The Physical Science Basis

Summary for Policymakers

Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change

This Summary for Policymakers was formally approved at the 10th Session of Working Group I of the IPCC, Paris, February 2007.

Note:
Text, tables and figures given here are final but subject to copy-editing.

Corrections made as of February 5th, 2007

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E-mail: IPCC-Sec@wmo.int Website: http://www.ipcc.ch

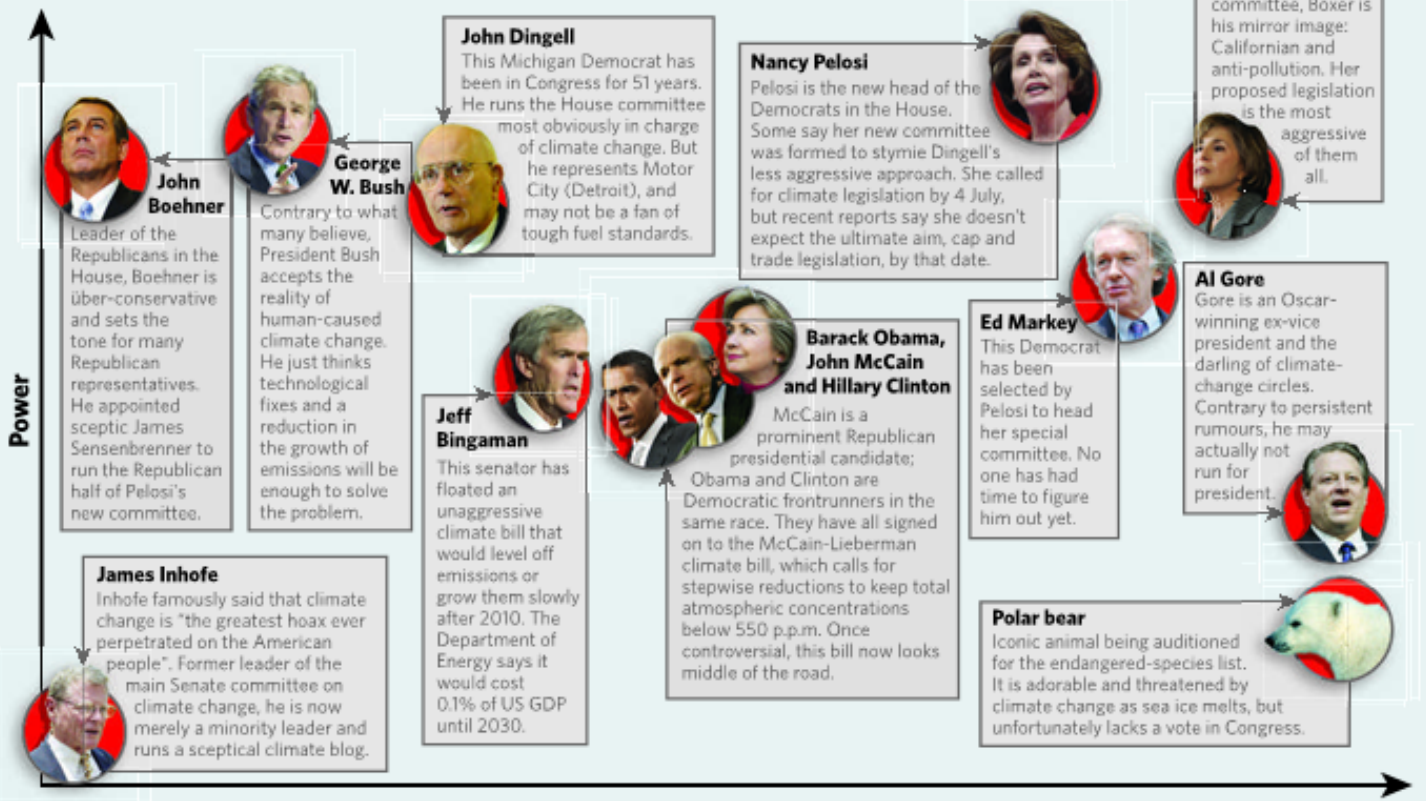
NCAR

The Government is coming around

GRAPHIC DETAIL

Where politicians stand on climate change

Since the Democrats took over the US House and Senate, ever more committees on climate change are holding hearings on a nearly daily basis. This month the leader of the House, Nancy Pelosi, formed yet another one, the Select Committee on Energy Independence and Global Warming, leaving even Washington energy analysts struggling to keep up with it all. **Emma Marris** charts the key players in terms of clout and greenness.



D. COOK/AP; J. ERNST/REUTERS; R. L. WOLLENBERG/UPI/NEWSCOM
S. J. FERRELL/CONGRESSIONAL QUARTERLY/NEWSCOM; M. SEGAR/REUTERS; S. WALSH/AP; D. MCNEW/GETTY
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S. SCHLIEBE/USFWS; R. SULLIVAN/AFP/GETTY; S. SCOTT/UPI/NEWSCOM; P. SAKUMA/AP; K. DIETSCH/UPI/NEWSCOM

The Energy Sector is Reversing Course

let's talk about climate change.

Much has been said recently about ExxonMobil and our views on climate change. So we'd like to take this opportunity to set out, clearly and concisely, our position on this important issue.

- The earth's climate has warmed about 0.7°C in the last century
- Many global ecosystems are showing signs of warming
- CO_2 emissions have increased

Climate science remains extraordinarily complex. So for over 15 years, our scientists have been participating directly in the preparation of the Intergovernmental Panel on Climate Change (IPCC) reports, which are an important contribution to climate science. In addition, we're already taking steps to address the challenge of reducing greenhouse gas emissions in effective and meaningful ways.
A few examples:

- We are working with governments and leading universities on technology breakthroughs to produce energy with reduced emissions
- We are working with auto and engine makers on programs that could improve fuel economy by as much as 30 percent
- We are working with academics, NGOs and governments to define meaningful policy approaches

Businesses, governments and NGOs are faced with a daunting task: selecting policies that balance economic growth and human development with the risks of climate change. The challenge is enormous, and we continue to work positively and constructively on meaningful approaches.
To learn more, go to exxonmobil.com/climate.

ExxonMobil
Taking on the world's toughest energy challenges.

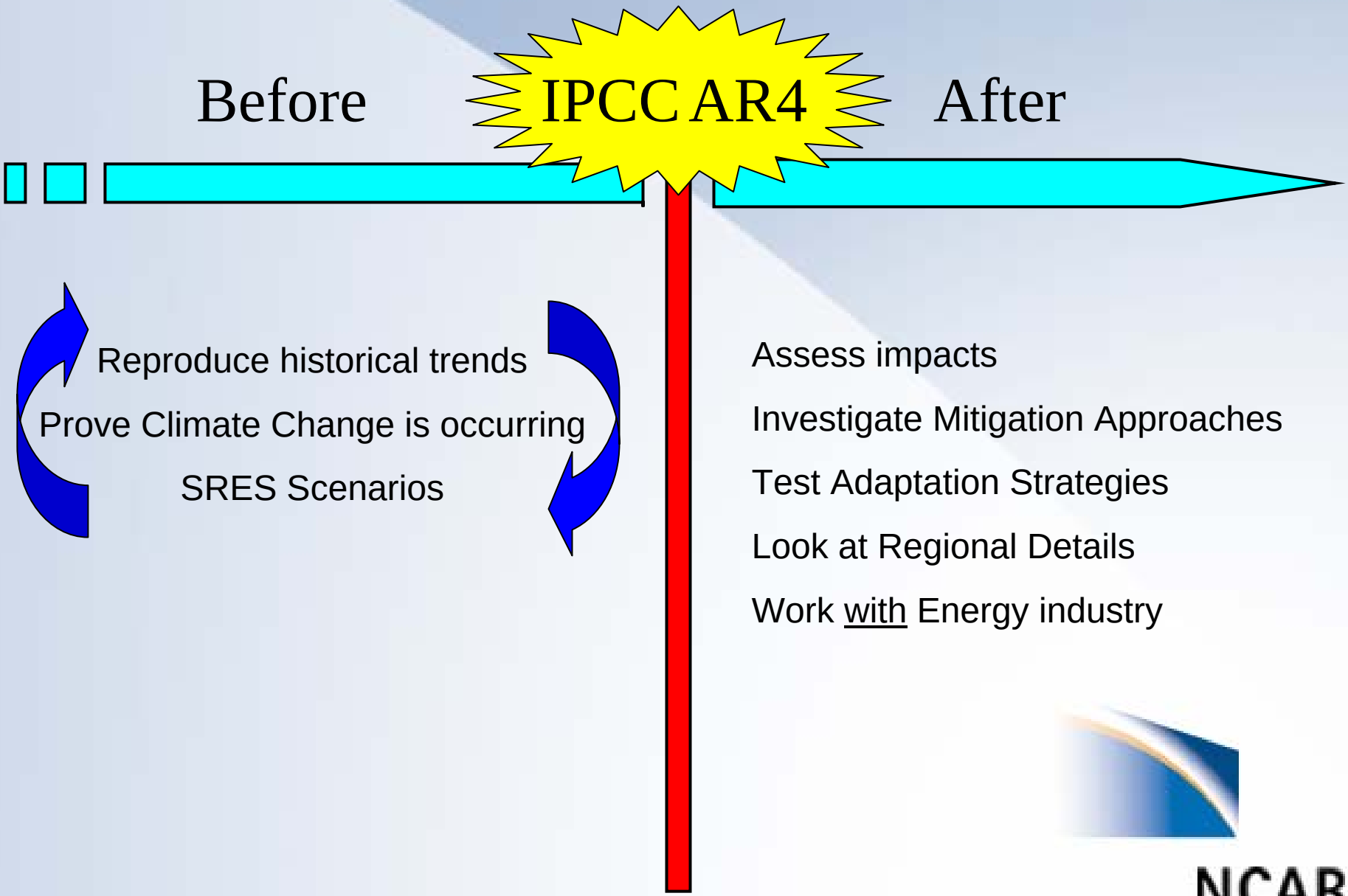
The Public is now engaging at a level never seen before

Strength and clarity of IPCC AR4 message due to

- Greater trust in our models
  - More realistic processes
  - Higher resolution
  - More ensembles -> less uncertainty
  - Long spin-ups
- Impossible without DOE collaboration
  - Scientific Development of the CCSM
  - Software engineers support
  - Raw computational horsepower

NCAR

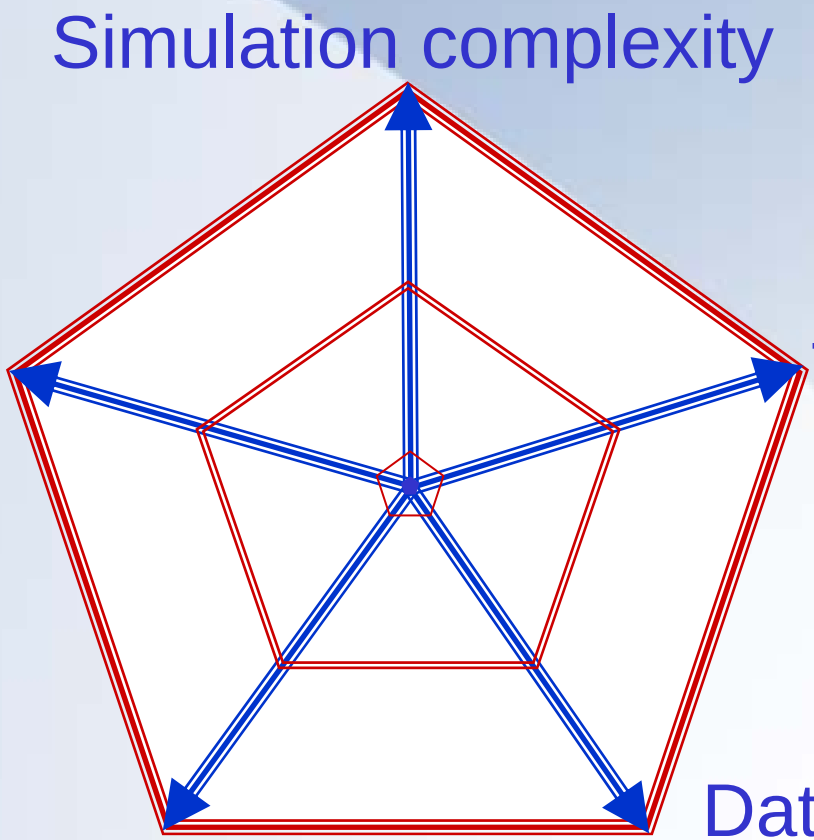
Climate Change Epochs



NCAR

5 HPC dimensions of Climate Prediction

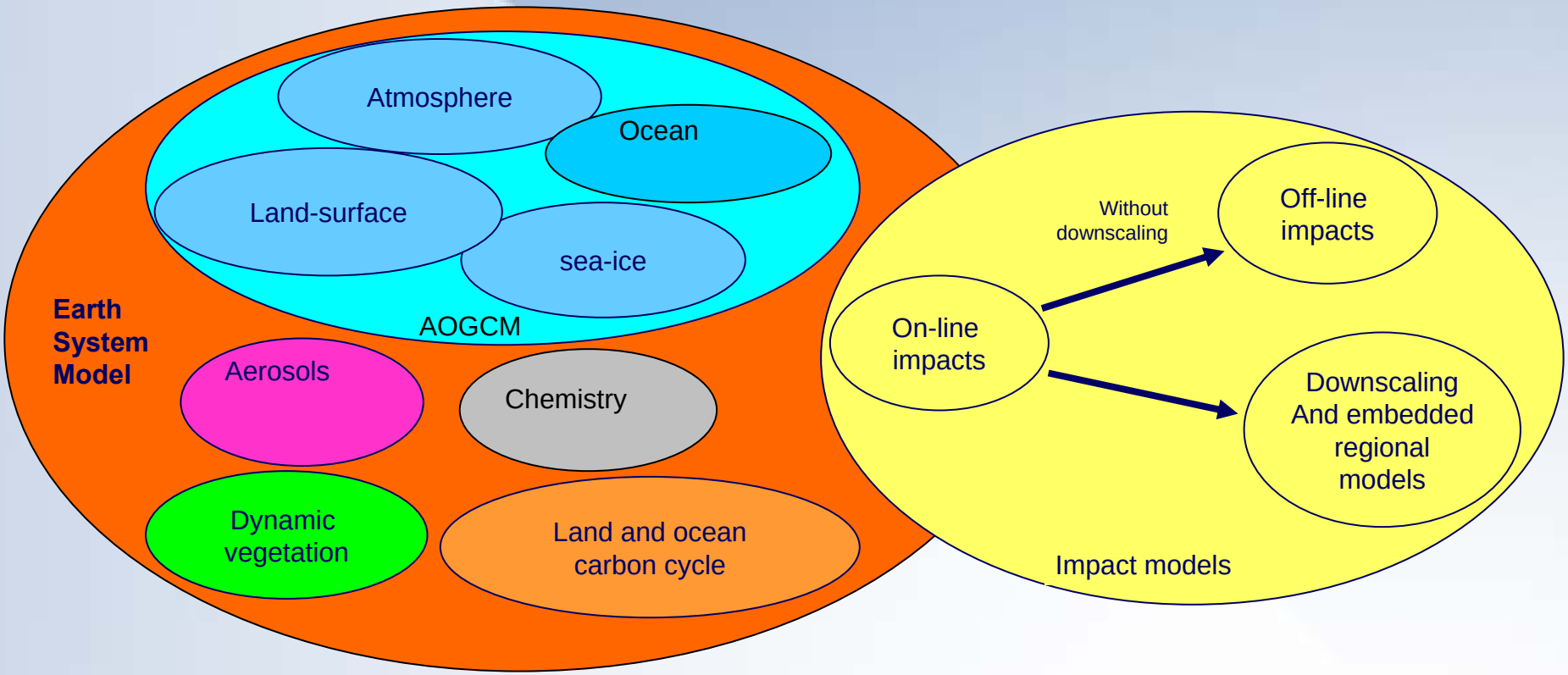
(Tim Palmer, ECMWF)



All require much greater computer resource and more efficient modelling infrastructures

NCAR

Earth System Models



Also…

- More sophisticated ocean ecosystems,
- Advanced vegetation dynamics
- Multiple crops and management types
- Impact of tropospheric ozone on vegetation
- Coastal zones
- Urban fractional cover
- River biogeochemistry
- Impacts of fire, etc…

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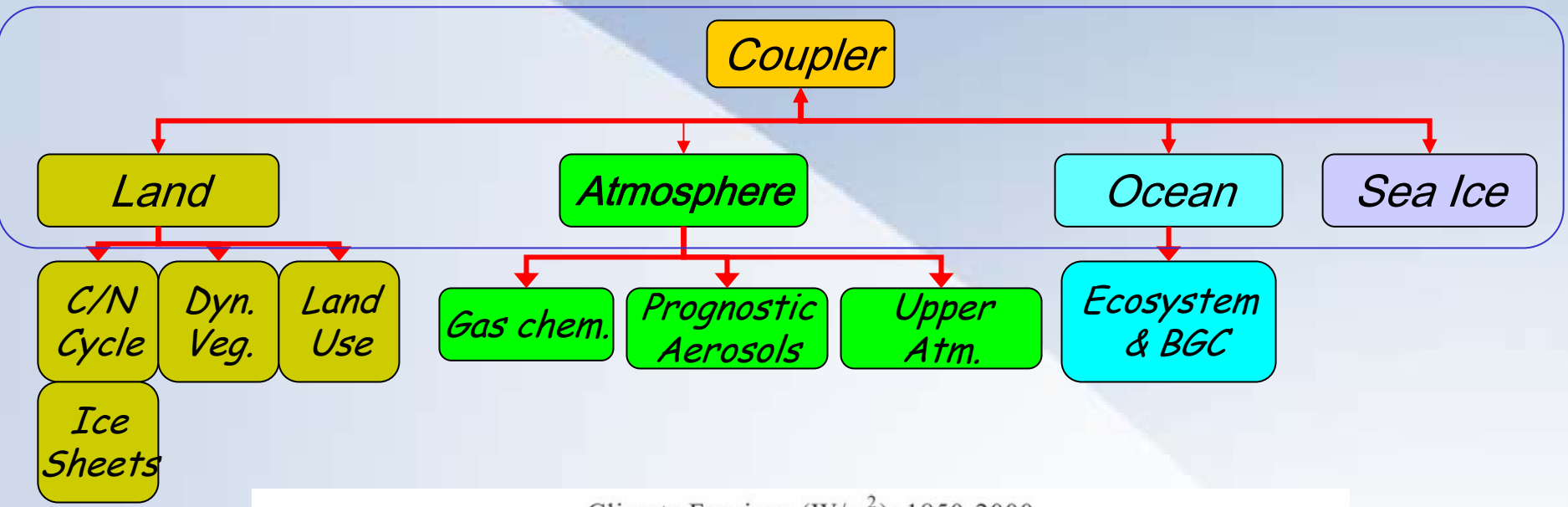
1st generation Earth System Model



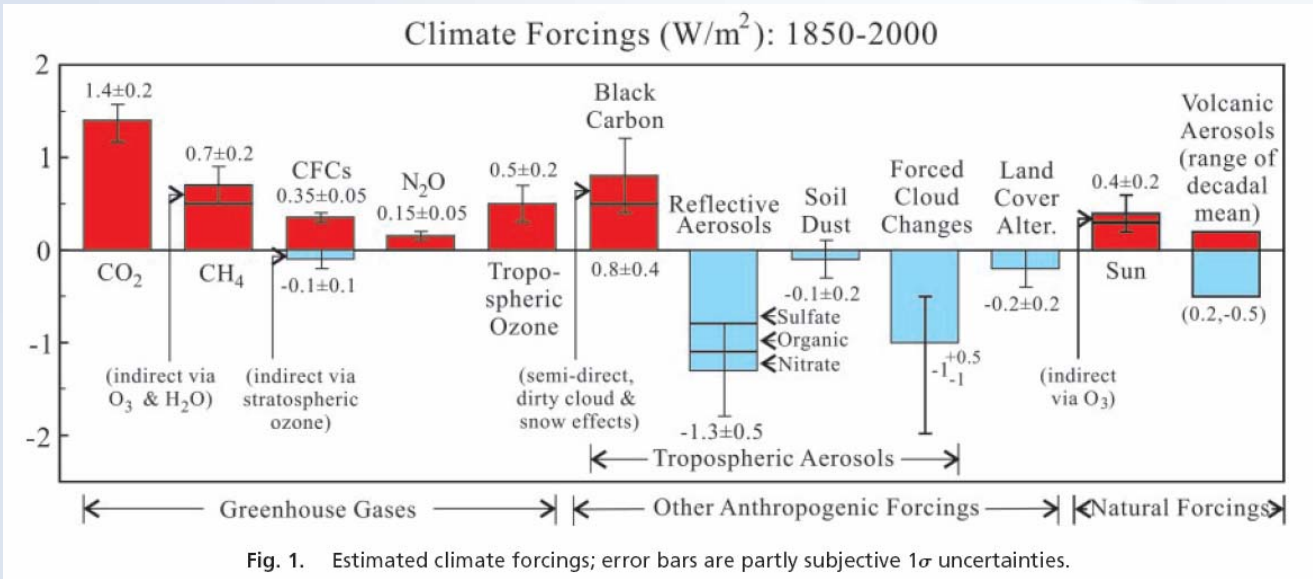
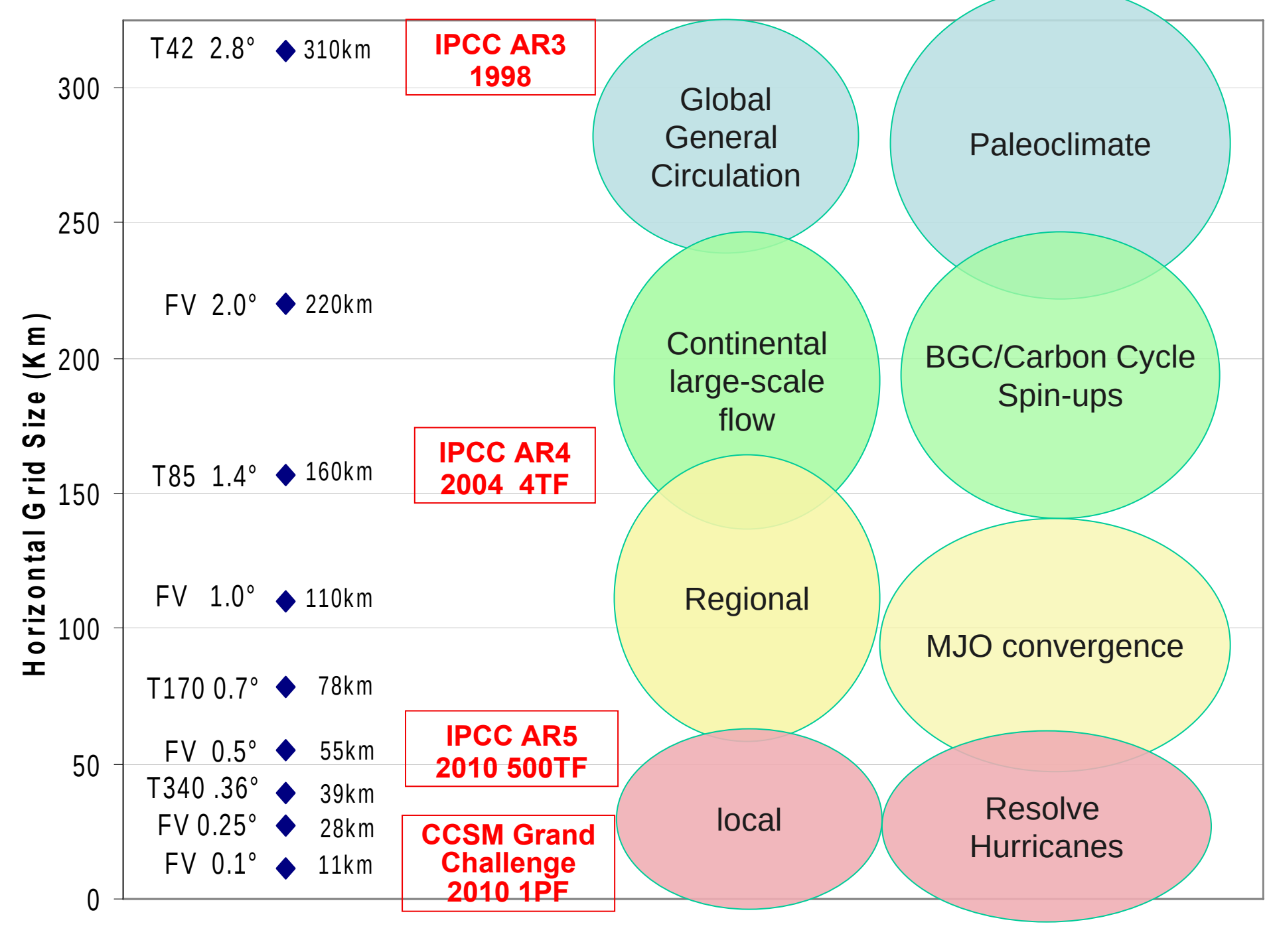
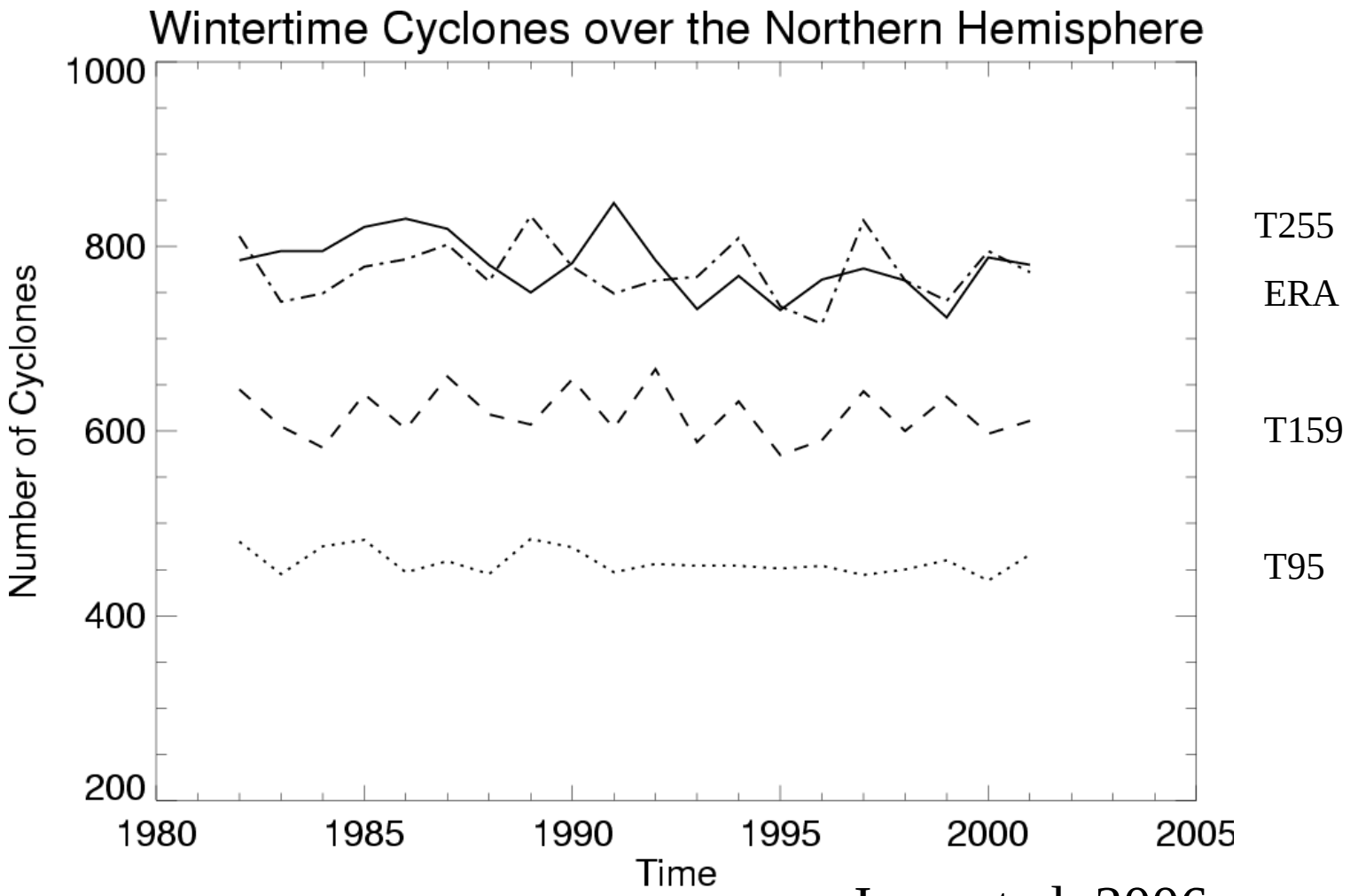


Fig. 1. Estimated climate forcings; error bars are partly subjective 1σ uncertainties.

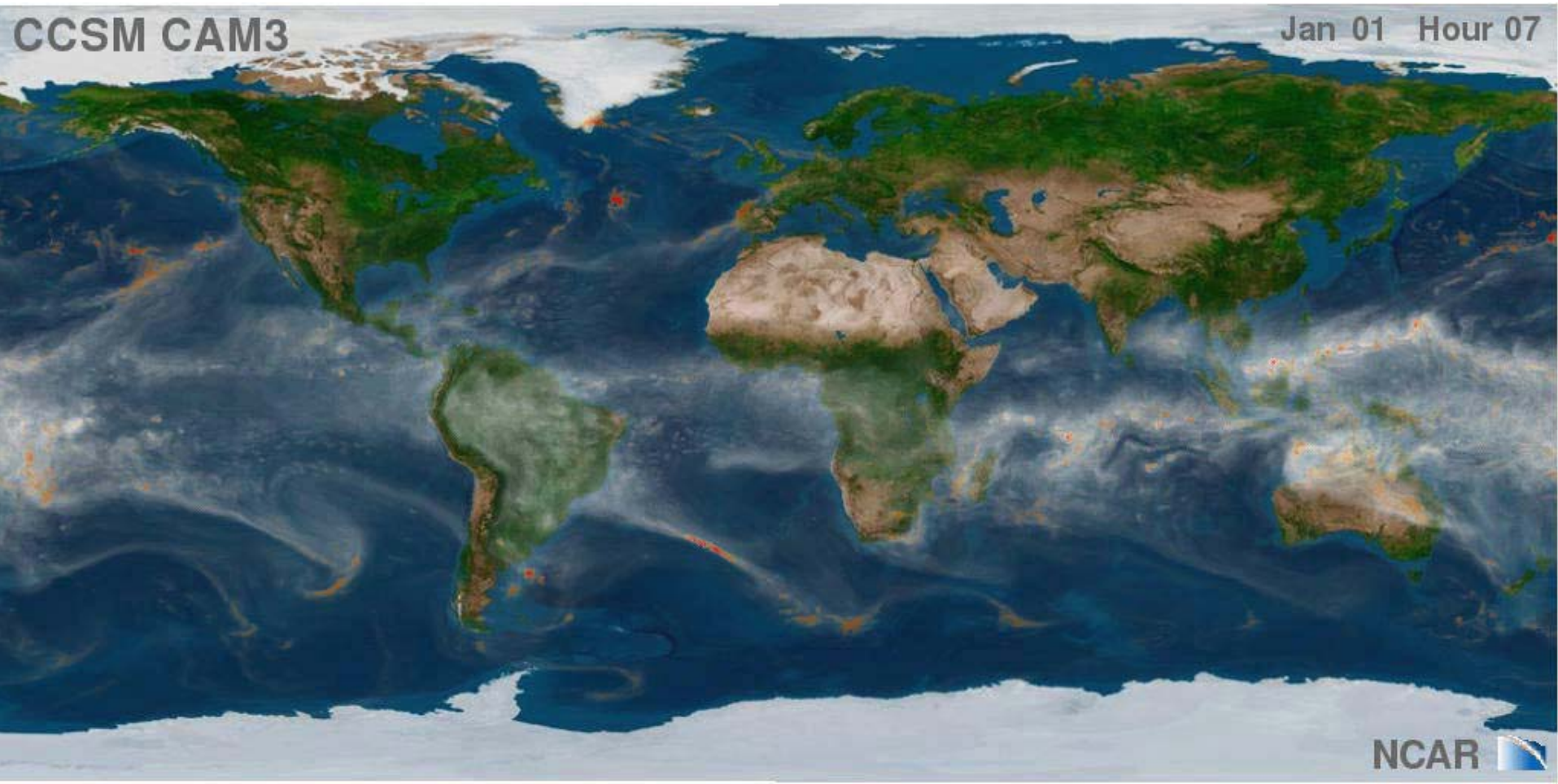
NCAR


Horizontal Grid Size (Km)
300
250
200
150
100
50
0
T42 2.8°
310km
FV 2.0°
220km
T85 1.4°
160km
FV 1.0°
110km
T170 0.7°
78km
FV 0.5°
55km
T340 .36°
39km
FV 0.25°
28km
FV 0.1°
11km
IPCC AR3 1998
IPCC AR4 2004 4TF
IPCC AR5 2010 500TF
CCSM Grand Challenge 2010 1PF
Global General Circulation
Paleoclimate
Continental large-scale flow
BGC/Carbon Cycle Spin-ups
Regional
MJO convergence
local
Resolve Hurricanes

Number of Northern Hemisphere Cyclones



Jung et al. 2006

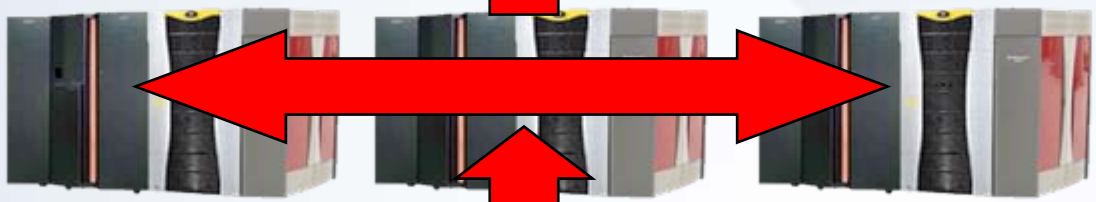

CCSM CAM3
Jan 01 Hour 07
NCAR

NSF Cyberinfrastructure General Purpose Platforms

Track-1
1Pf sustained

2009-2011

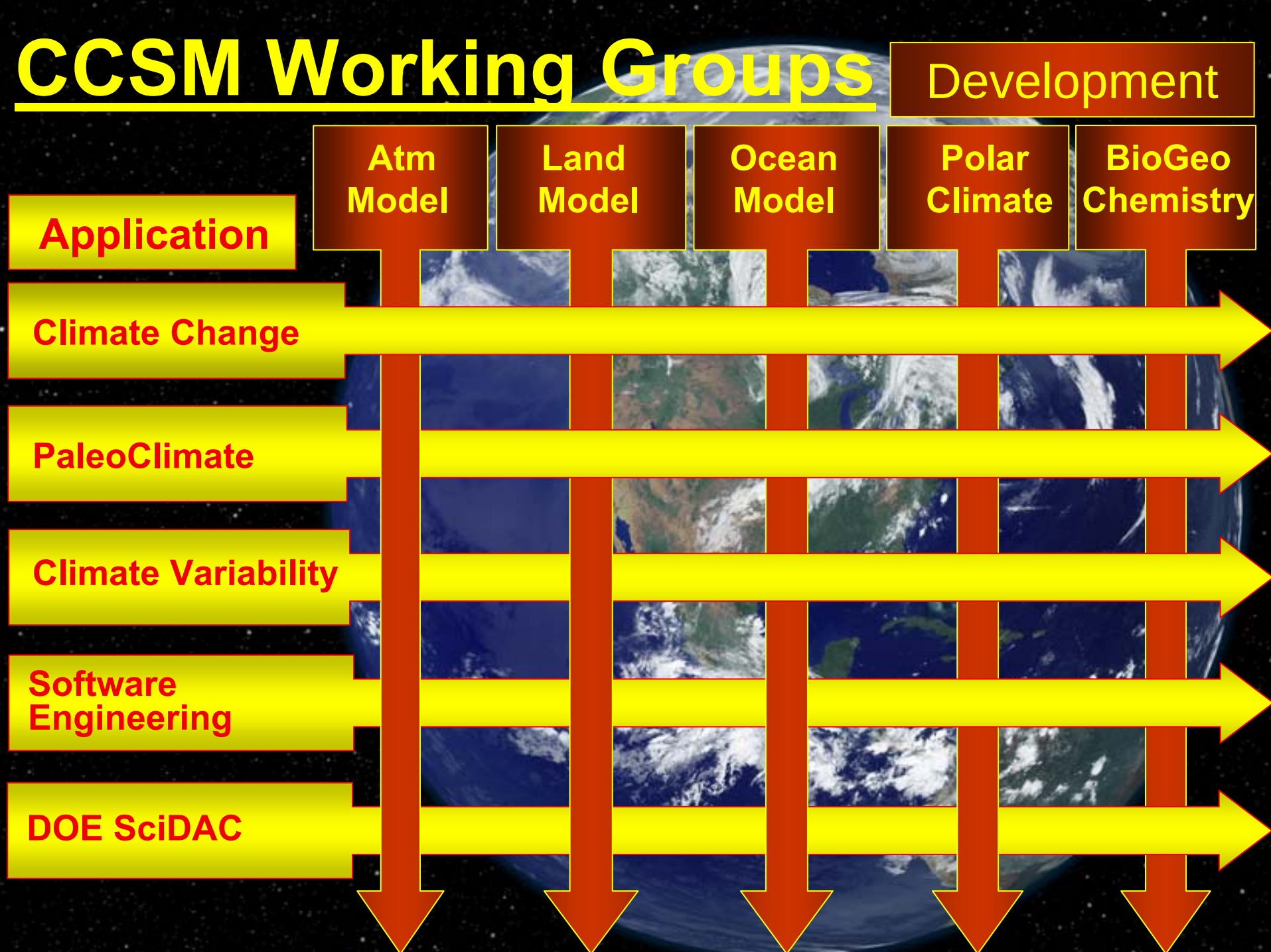
Track-2
100 Tf



Track-3

NCAR

CCSM Working Groups



Petascale Climate Simulations

- Topic 1. Across scale modeling: simulation of the 21st century climate with a coupled atmosphere-ocean model at 0.1 degree resolution (eddy resolving in the ocean). For specific time periods of the integration, shorter-time simulations with higher spatial resolution: 1 km with a nonhydrostatic global atmospheric model and 100 m resolution in a nested regional model. Emphasis will be put the explicit representation of moist turbulence, convection and hydrological cycle.

- Topic 2. Interactions between atmospheric layers and response of the atmosphere to solar variability. Simulations of the atmospheric response to 10-15 solar cycles derived by a high-resolution version of WACCM (with explicit simulation of the QBO) coupled to an ocean model.

Community Climate System Model (CCSM)

Current Configuration

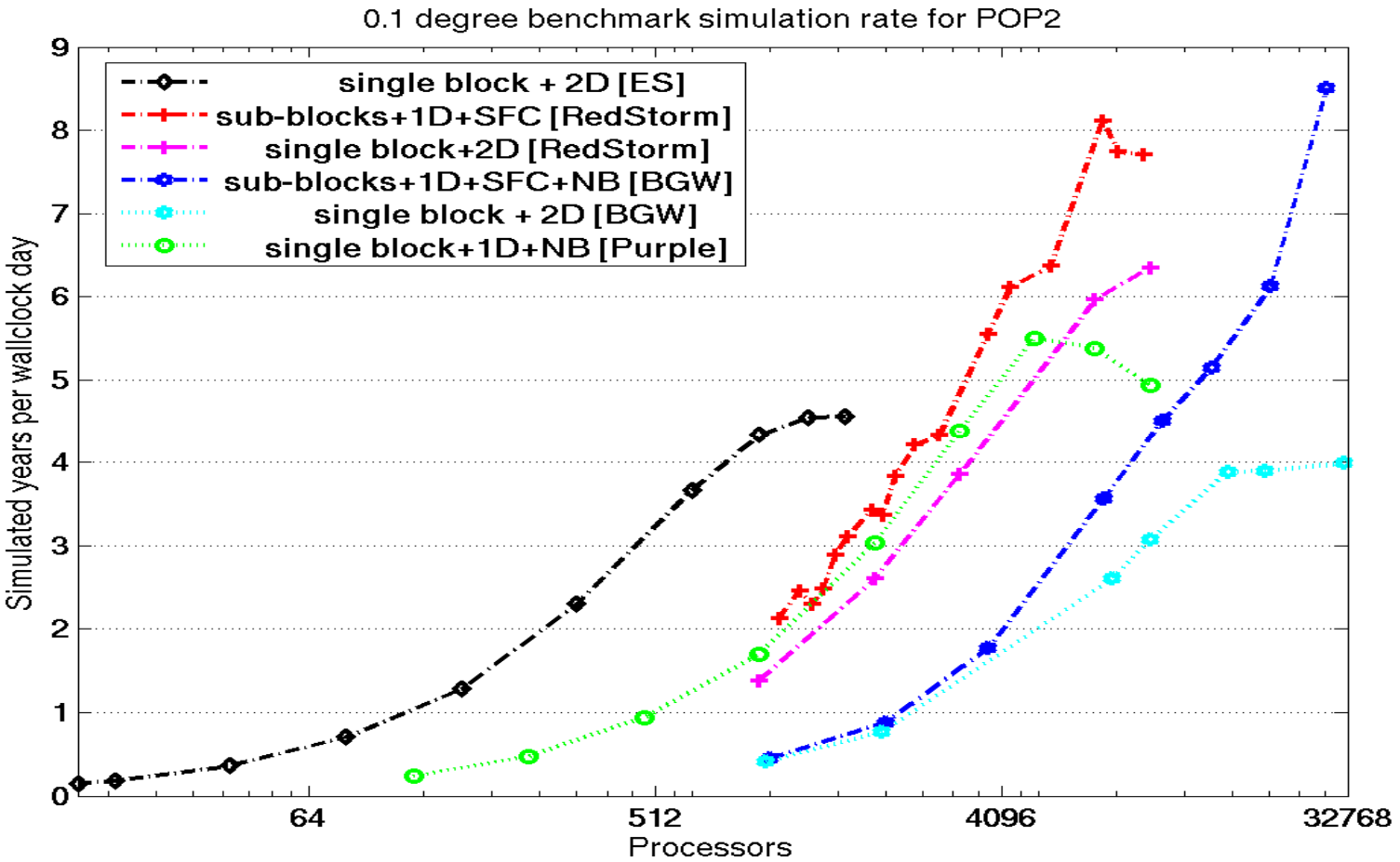
- Hub and spoke design with single or multiple executables
- Exchange boundary information through coupler
- Each code quite large: 60-200k lines per code
- Need 5 simulated years/day --> Must run at “low” resolution
- Standard configuration run at scaling sweetspot of O(200) processors

Petascale Configuration

- Single executable at ~5 years wall-clock day
- Targeting 10K - 120K processors per simulation
  - CAM @ 0.25° (30 km, L66)
  - POP @ 0.1° Demonstrated 8.5 years/day on 28K Bluegene
  - Sea-Ice @ 0.1° Demonstrated 42 years/day on 32K Bluegene
  - Land @ 0.1°
  - Cpl

NCAR

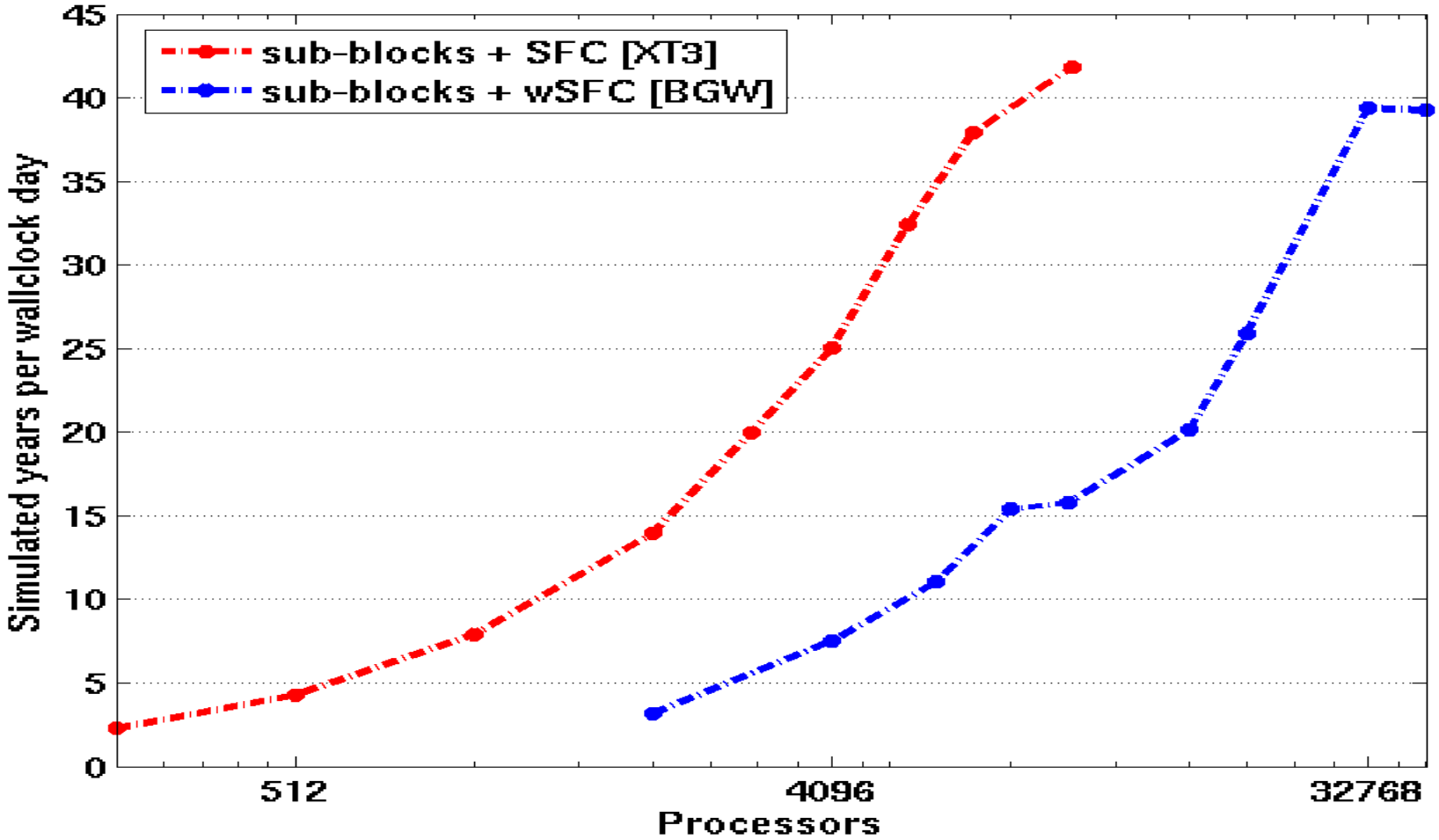
POP 0.1° benchmark



Courtesy of J. Dennis, Y. Yoshida, M. Taylor, P. Worley

NCAR

CICE4 @ 0.1°



Courtesy of John Dennis

NCAR

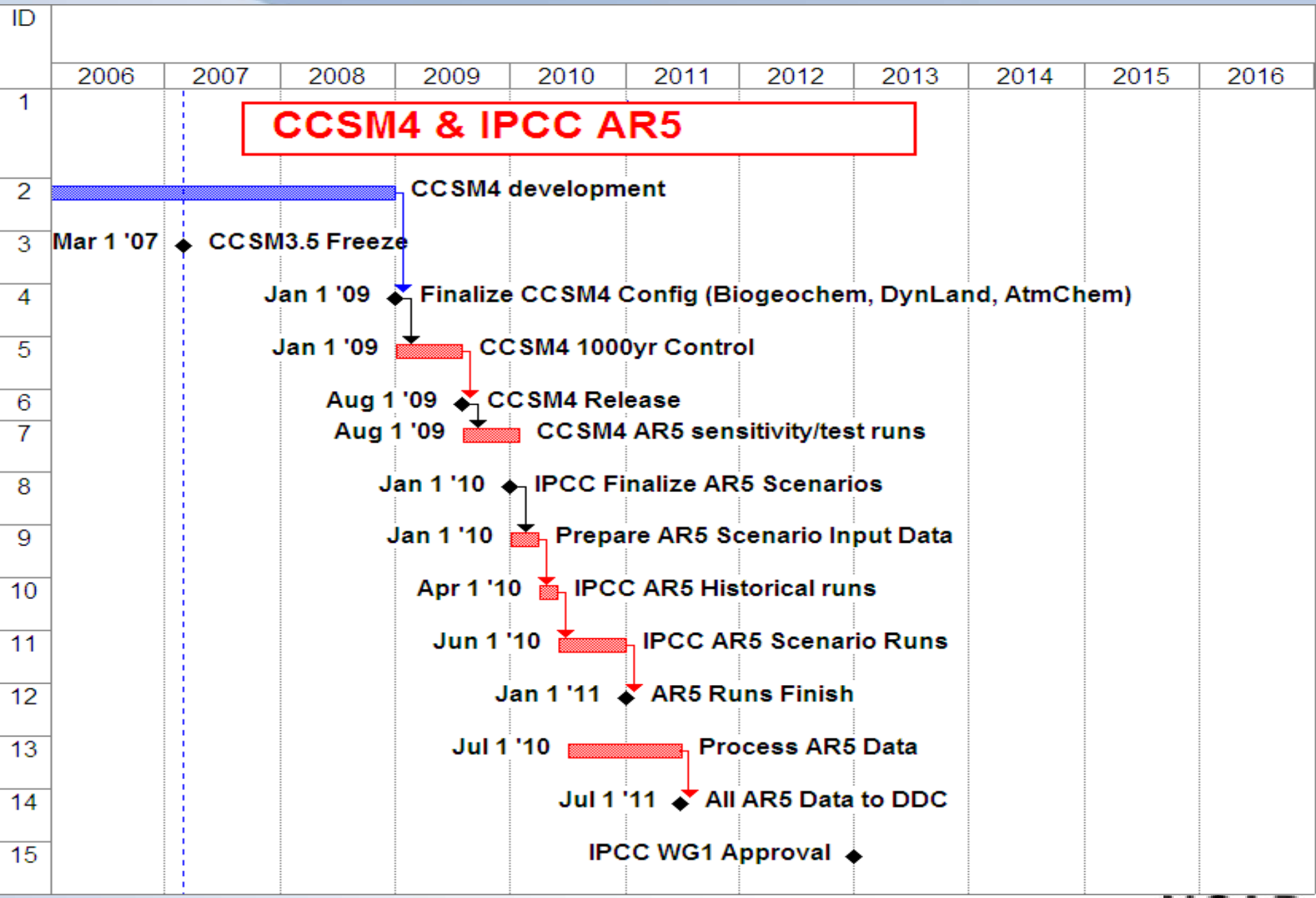
Moving to the Petascale

- **Scientific goals:**
  - Seamless downscaling, integrated weather and climate modeling
  - Earth system modeling at eddy-resolving scale
  - Climate “snap shots” at cloud resolving scale
- **Computing:**
  - We must move to MPP with >10K processing elements (PEs) soon.
  - Systems now have 5-30K PEs, seeing success porting to these platforms.
- **Challenges:**
  - Skilled personnel for code development on these platforms
  - Scalable numerics and analysis techniques
  - Robust and fault-tolerant communication frameworks
  - HPC platforms can be very fragile
- **Common issues for all component models:**
  - Parallel IO
  - Eliminate all serial code
  - Memory usage

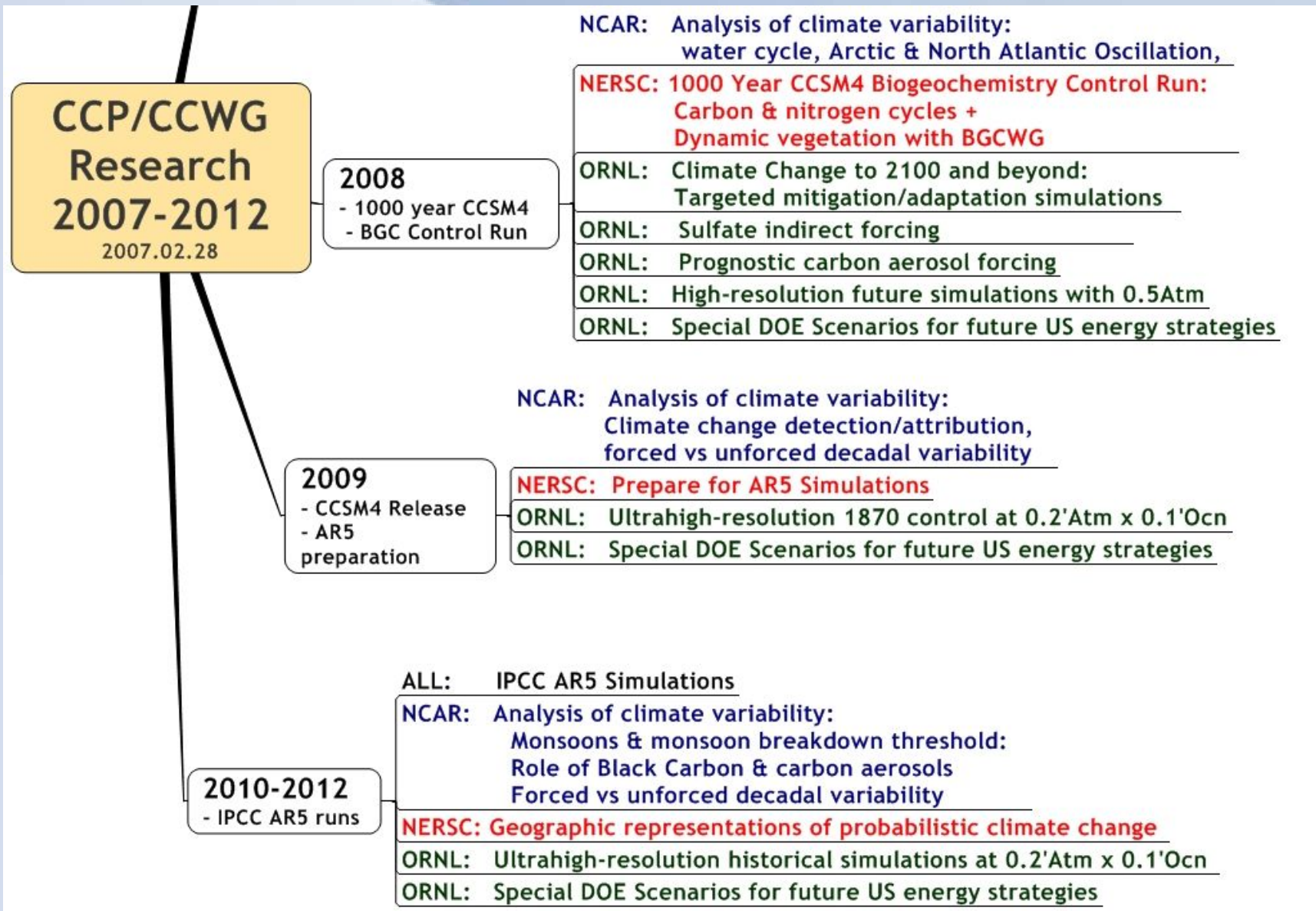
- **Petascale box ≠ Petascale science**

NCAR

Next Steps

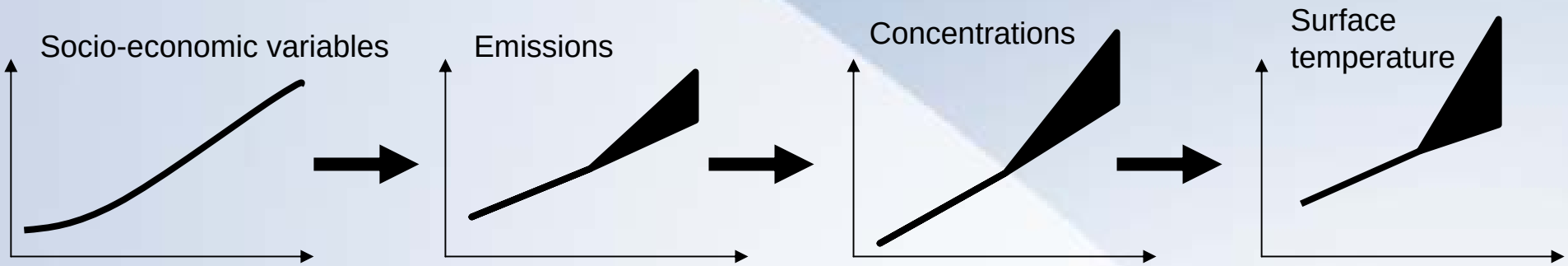

ID
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
1
CCSM4 & IPCC AR5
2
CCSM4 development
3
Mar 1 '07
CCSM3.5 Freeze
4
Jan 1 '09
Finalize CCSM4 Config (Biogeochem, DynLand, AtmChem)
5
Jan 1 '09
CCSM4 1000yr Control
6
Aug 1 '09
CCSM4 Release
7
Aug 1 '09
CCSM4 AR5 sensitivity/test runs
8
Jan 1 '10
IPCC Finalize AR5 Scenarios
9
Jan 1 '10
Prepare AR5 Scenario Input Data
10
Apr 1 '10
IPCC AR5 Historical runs
11
Jun 1 '10
IPCC AR5 Scenario Runs
12
Jan 1 '11
AR5 Runs Finish
13
Jul 1 '10
Process AR5 Data
14
Jul 1 '11
All AR5 Data to DDC
15
IPCC WG1 Approval

Next Steps

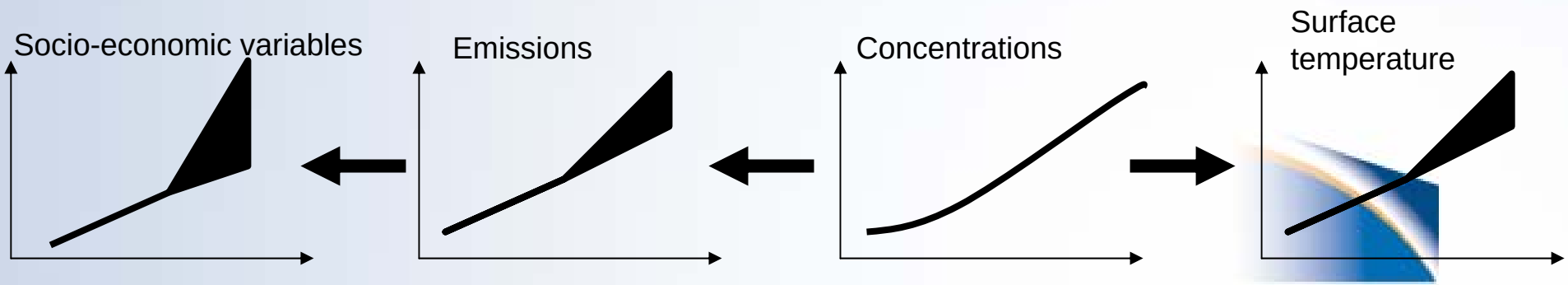

CCP/CCWG Research 2007-2012
2007.02.28
2008
- 1000 year CCSM4
- BGC Control Run
NCAR: Analysis of climate variability: water cycle, Arctic & North Atlantic Oscillation,
NERSC: 1000 Year CCSM4 Biogeochemistry Control Run: Carbon & nitrogen cycles + Dynamic vegetation with BGCWG
ORNL: Climate Change to 2100 and beyond: Targeted mitigation/adaptation simulations
ORNL: Sulfate indirect forcing
ORNL: Prognostic carbon aerosol forcing
ORNL: High-resolution future simulations with 0.5Atm
ORNL: Special DOE Scenarios for future US energy strategies
2009
- CCSM4 Release
- AR5 preparation
NCAR: Analysis of climate variability: Climate change detection/attribution, forced vs unforced decadal variability
NERSC: Prepare for AR5 Simulations
ORNL: Ultrahigh-resolution 1870 control at 0.2'Atm x 0.1'Ocn
ORNL: Special DOE Scenarios for future US energy strategies
2010-2012
- IPCC AR5 runs
ALL: IPCC AR5 Simulations
NCAR: Analysis of climate variability: Monsoons & monsoon breakdown threshold: Role of Black Carbon & carbon aerosols Forced vs unforced decadal variability
NERSC: Geographic representations of probabilistic climate change
ORNL: Ultrahigh-resolution historical simulations at 0.2'Atm x 0.1'Ocn
ORNL: Special DOE Scenarios for future US energy strategies

21st Century Experiments:
Long term (to 2100 and beyond))

- Forward approach: uncertainties build up; start with socioeconomic variables



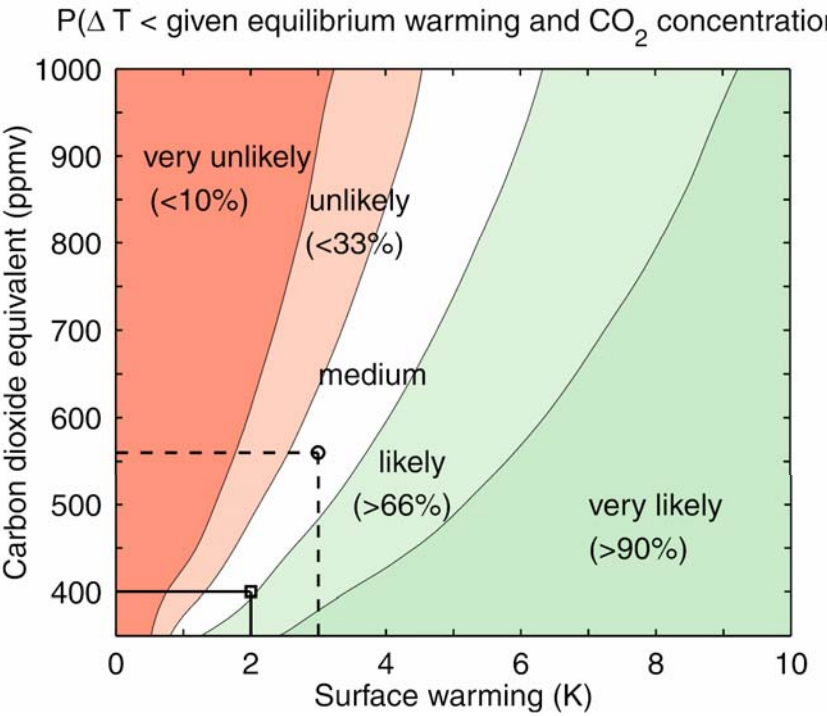
- Reverse approach: uncertainties go both ways; start with stabilization scenario concentrations, work back to emissions and socio-economic conditions



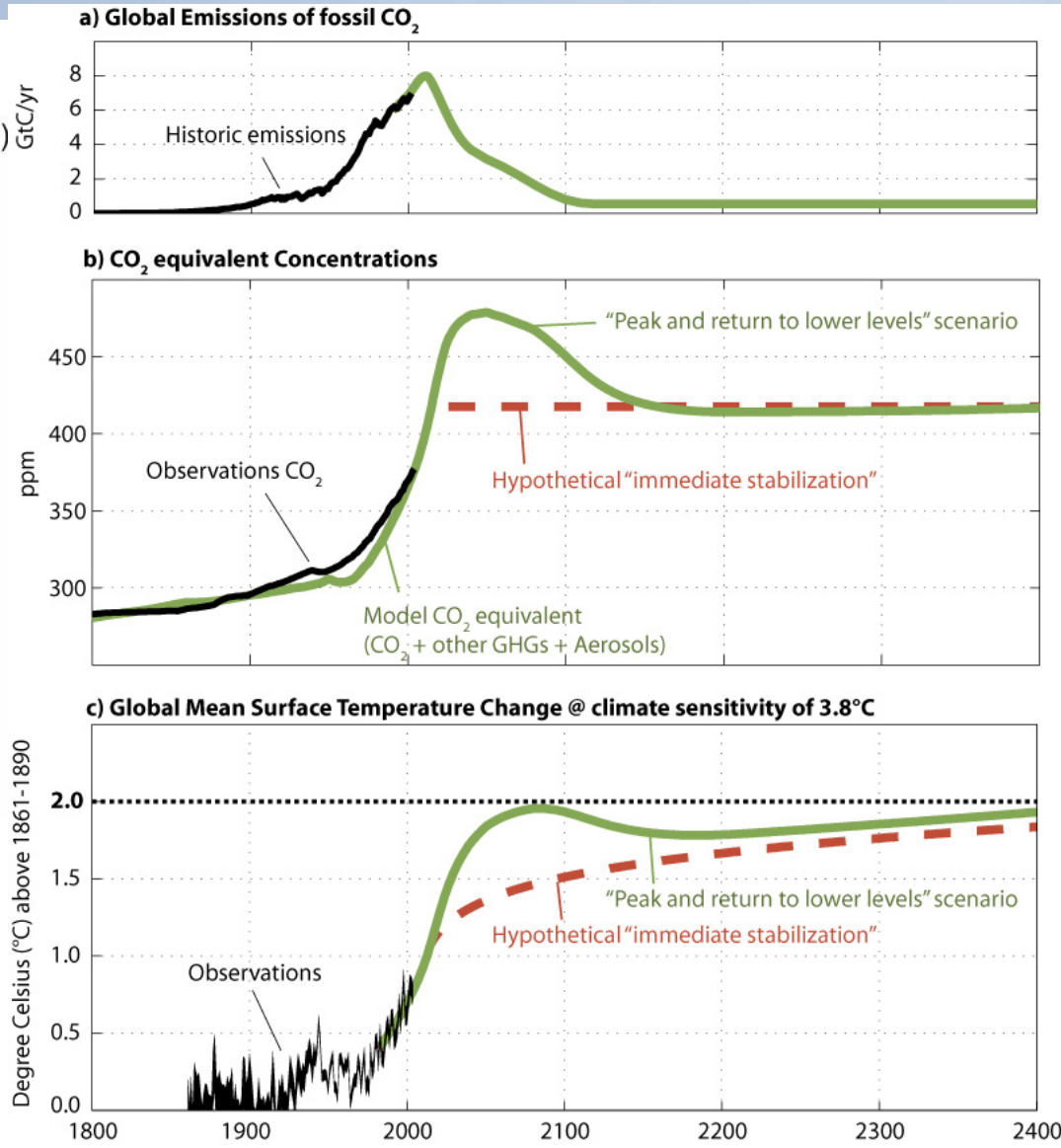
NCAR

A short overshoot of atmospheric CO_2 might be compatible with the 2°C target.

Likelihood of warming



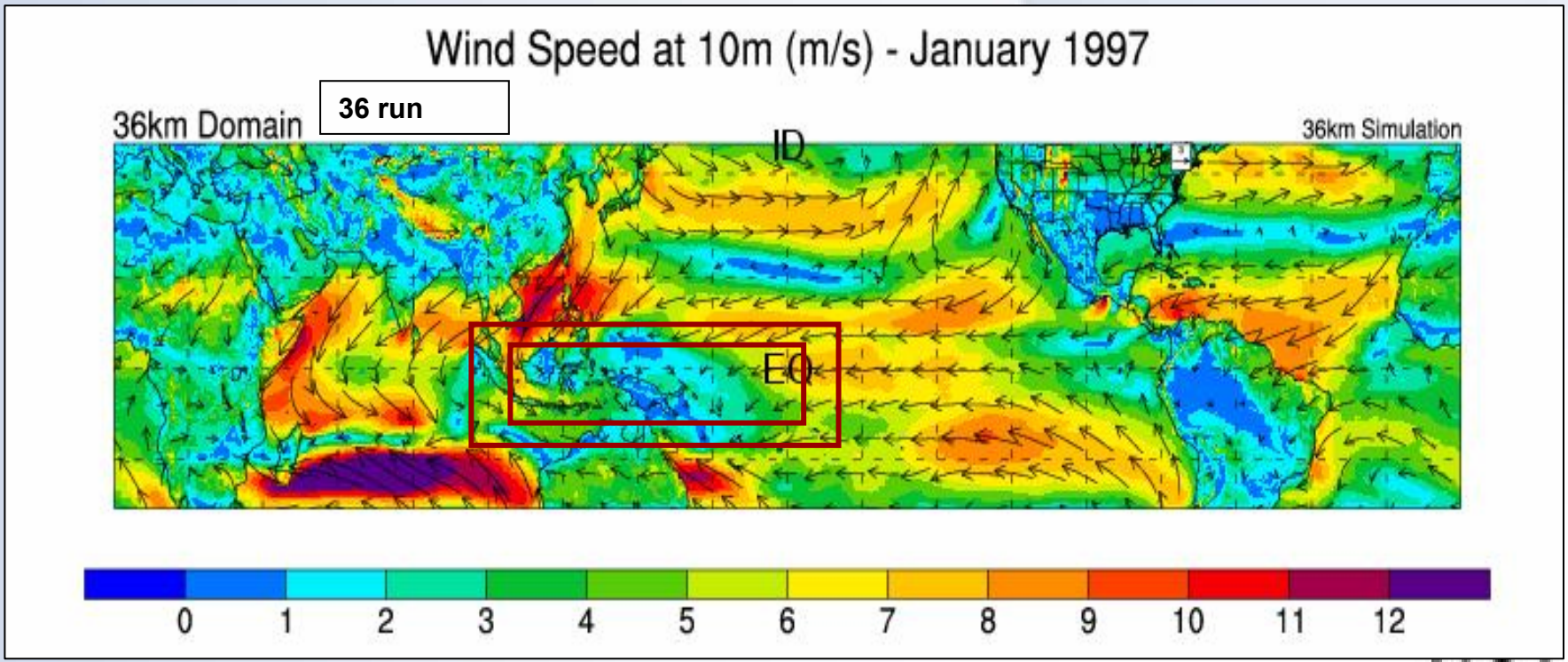
- Stabilizing temperature requires stabilizing atmospheric CO2,
- Limiting warming to 2°C requires stabilization at 400-450ppm CO2



Nested Regional Climate Model

Joint initiative: MMM, CGD and PNL:

- ***First Step: Downscaling for US climate forecasting;***
- ***Second Step: Tropical Channel Model with 2-way nested high-resolution grids to investigate development and role of tropical modes and scale interactions;***
- ***Next Step: Fully nested within CAM and CCSM in 2-way interactive mode.***



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NSF Geosciences CyberCollaboratory

Binding together Geosciences Research Community Resources…

Other National Labs and Supercomputer Centers, Grids and International Alliances

Geo-related Collaboratories, virtual org.

Earth Interiors Resource Center

Minority Serving Institution Resource Center

Energy Research Resource Center

Atmospheric Science Resource Center

NSF Geosciences CyberCollaboratory

Ocean Science Resource Center

Data/ Visualization Resource Center(s)

Observational Systems

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Closing Comments

Climate Sciences has coming of age through both intellectual and infrastructural advances. It is clear that not that many high-capability Earth System Modeling centers can be afforded worldwide, with all the needed features. Collaborations are the only way to achieve this.

- Community earth system model suites
- HPC and Grid computing
- Intellectual Partnership
- Data management, analysis and visualization systems
- A World-class Collaboratory

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Thanks! Any Questions?


APRIL 3, 2006
www.time.com AOL Keyword: TIME
SPECIAL REPORT GLOBAL WARMING
TIME
BE WORRIED. BE VERY WORRIED.
Climate change isn't some vague future problem—it's already damaging the planet at an alarming pace. Here's how it affects you, your kids and their kids as well
EARTH AT THE TIPPING POINT
HOW IT THREATENS YOUR HEALTH
HOW CHINA & INDIA CAN HELP SAVE THE WORLD—OR DESTROY IT
THE CLIMATE CRUSADERS

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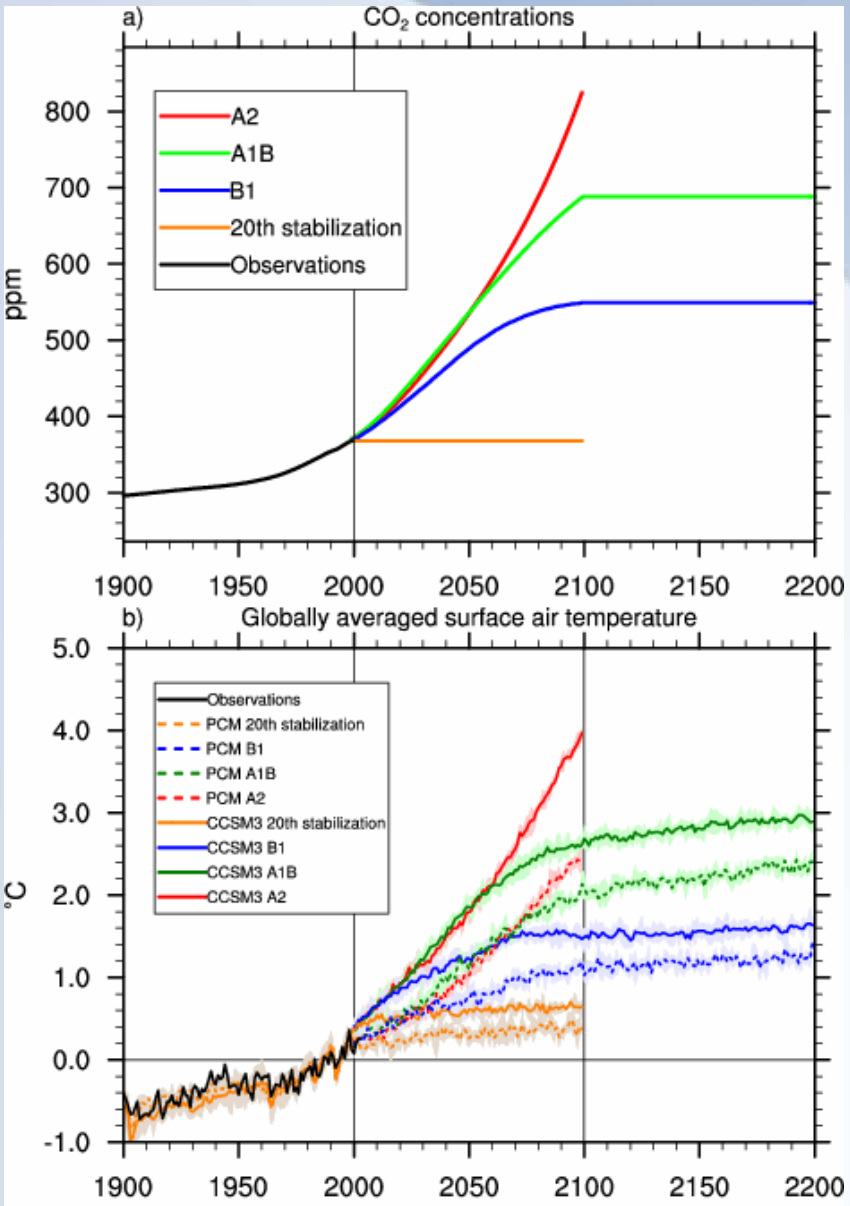
Lessons from the Past



Significant changes observed at 4x CO2

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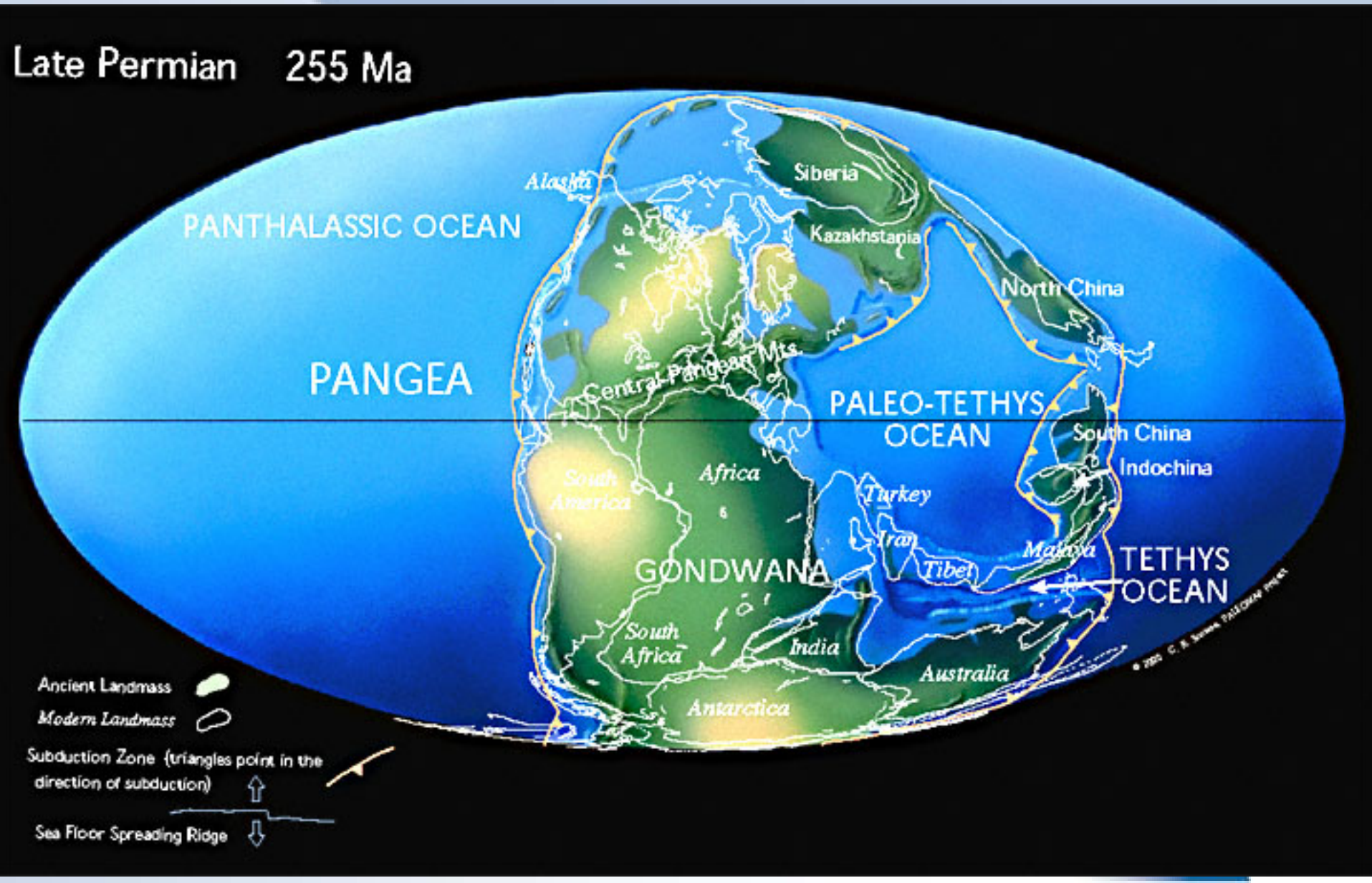
Late Permian 255 Ma
PANTHALASSIC OCEAN
PANGEA
Alaska
Siberia
Kazakhstania
North China
Central Pangean Mts.
PALEO-TETHYS OCEAN
South China
Indochina
South America
Africa
Turkey
Iran
Malaya
Tibet
TETHYS OCEAN
GONDWANA
South Africa
India
Australia
Antarctica
Ancient Landmass
Modern Landmass
Subduction Zone (triangles point in the direction of subduction)
Sea Floor Spreading Ridge

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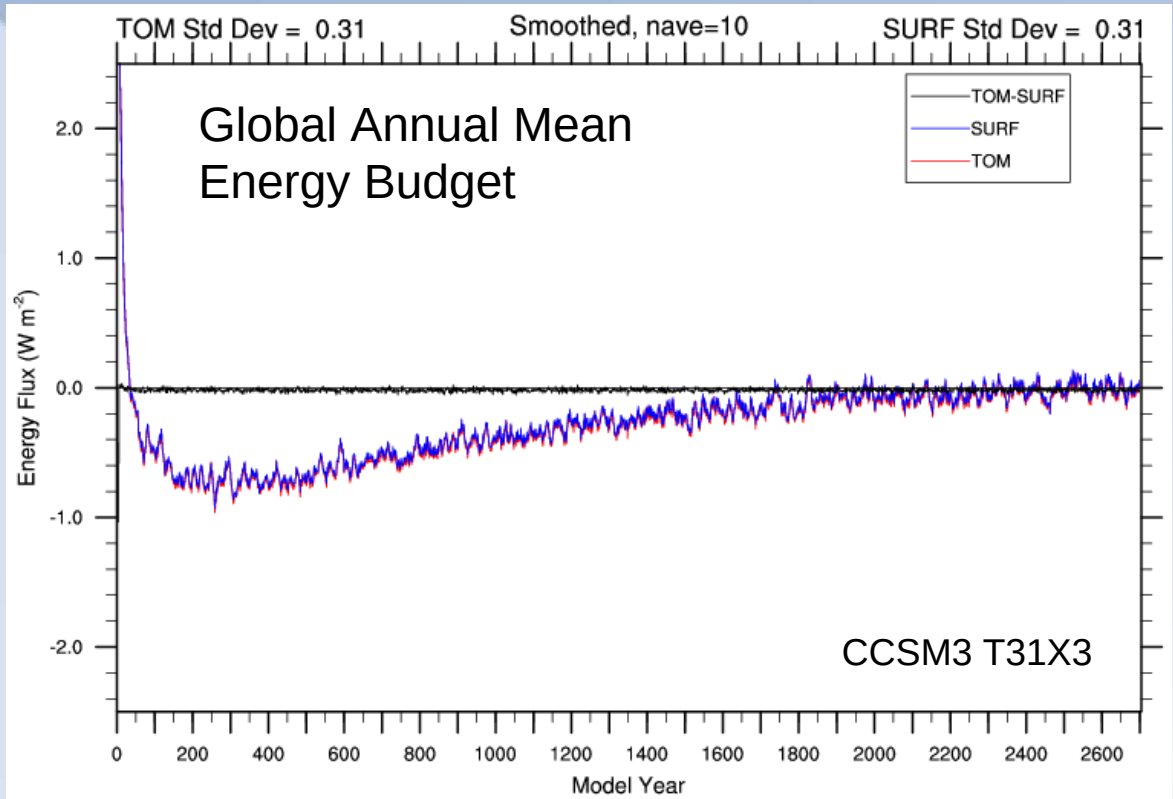
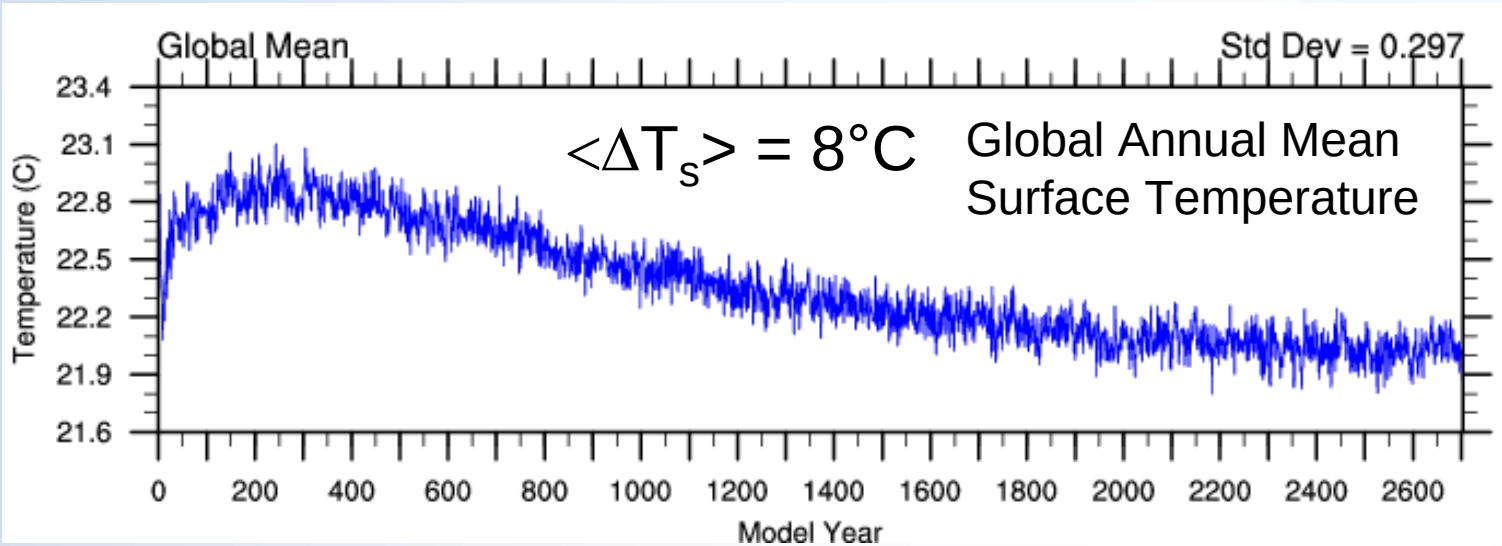
Forcing of 10X increase in CO_2 and Permian paleogeography



Permian coupled model run for 2700 years to new equilibrium state

Kiehl and Shields



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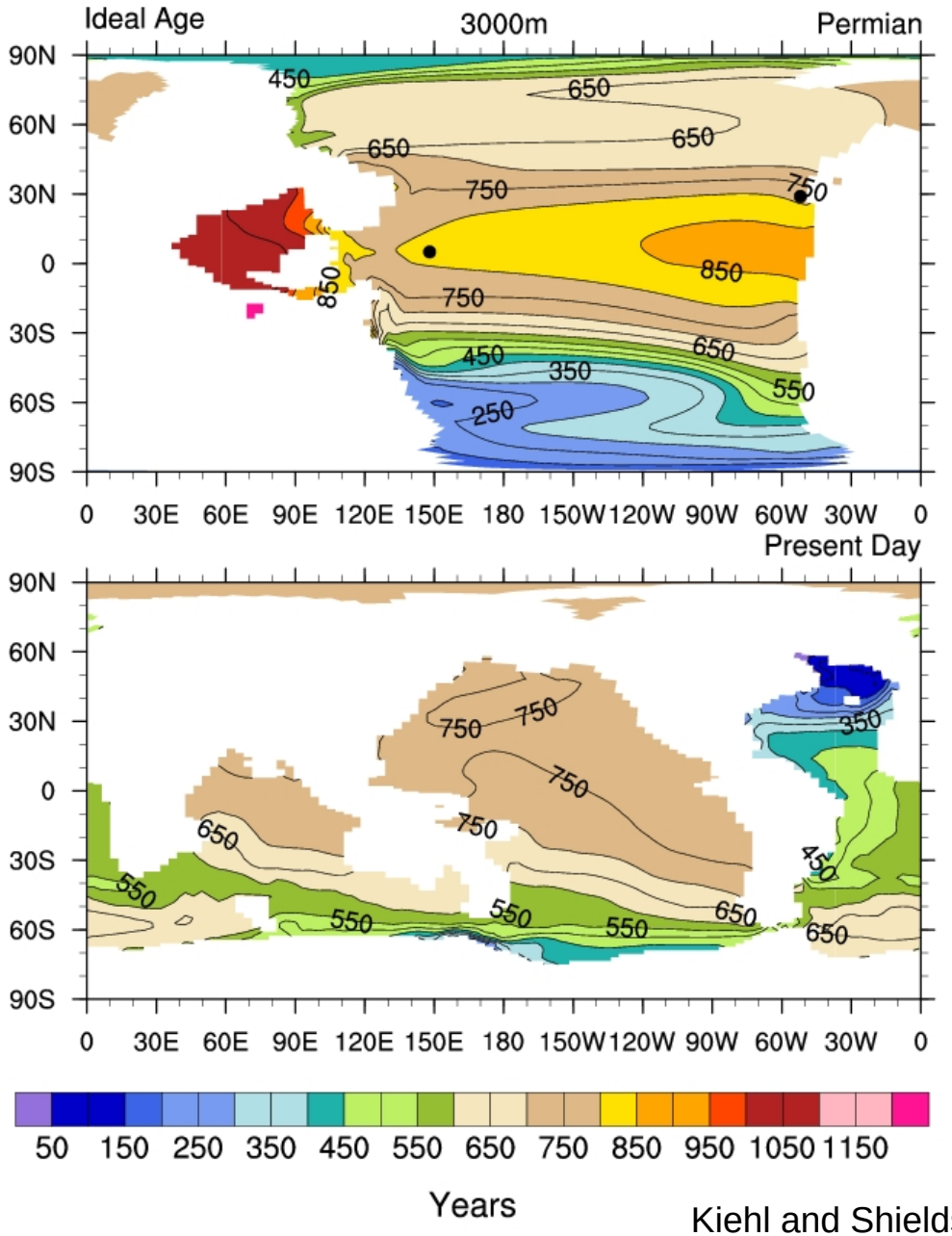
Inefficient mixing in Permian ocean indicative of anoxia, consistent with large extinction event



Kiehl and Shields (2005)

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- Clear evidence
- Some evidence
- No evidence

	Global warming	Oceanic anoxia	Methane release from gas hydrates	Oceanic calcification crisis	Significant extinction event
North Atlantic (55 Ma)		Palaeocene/ Eocene boundary			
Deccan (65 Ma)					End-Cretaceous (K/T)
Caribbean–Colombian, Madagascar (90 Ma)		End-Cenomanian Stage			
Ontong Java (120 Ma)		Early Aptian Stage			
Paraná–Etendeka (133 Ma)		Valanginian Stage			
Karoo–Ferrar (180 Ma)					Toarcian Stage
CAMP (200 Ma)					End-Triassic (T/J)
Siberian (250 Ma)					End-Permian (P/T)
Emeishan (258 Ma)					End-Guadalupian

Wignall(2005)

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Supercomputers at ORNL

50 TF Cray XT3

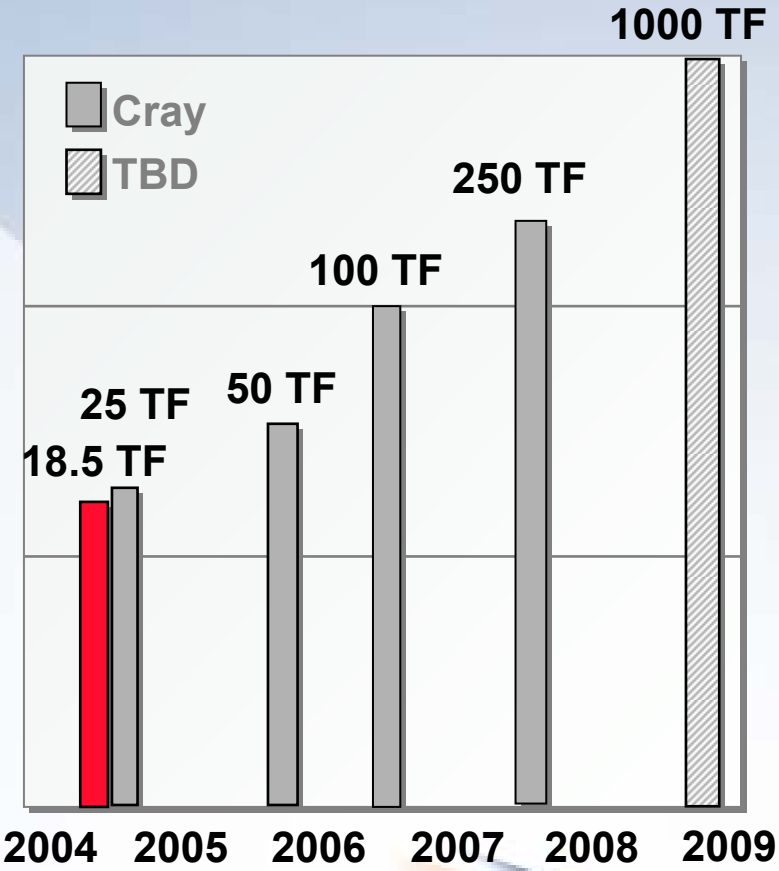
- 5212 dual core Opterons
- 21 Terabytes memory
- 100TB scratch

60 TF Cray XT4

- 6296 dual core Opterons
- New interconnect
- Acceptance testing

18 TF Cray X1 / X1E

- Will not expand
- 1024 processors
- Vector processing for sustained performance



Courtesy of John Drake (ORNL)

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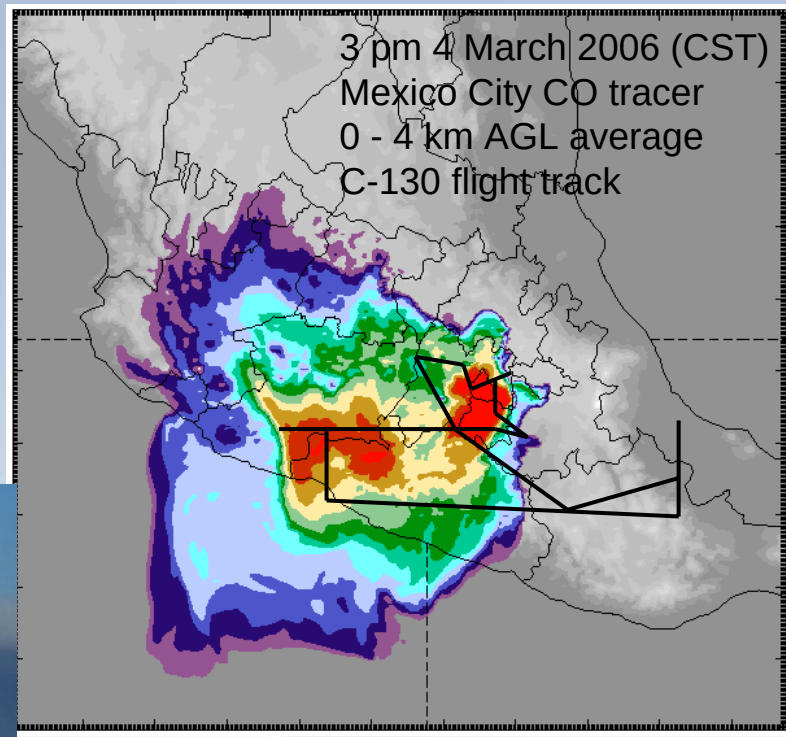
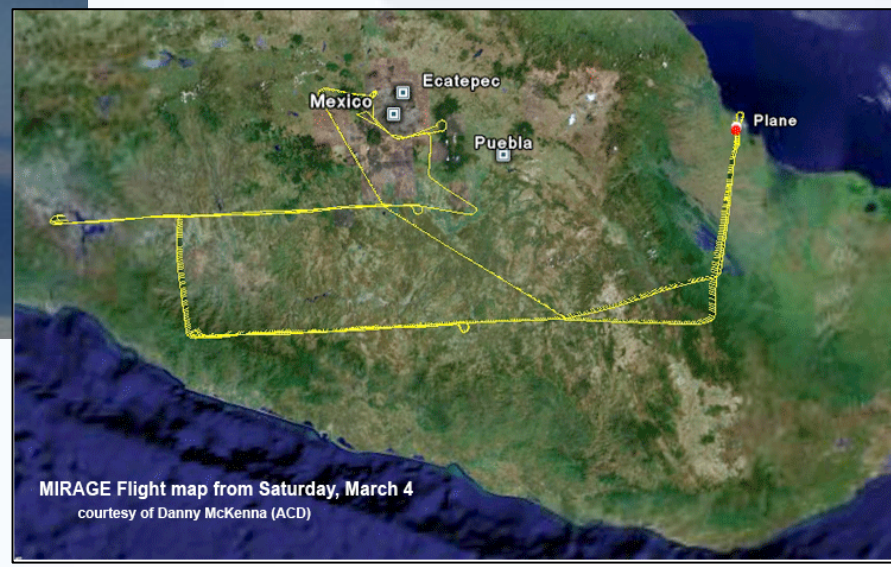
ARW forecast for MIRAGE

Field campaign: 1 - 28 March 2006

Mexico City pollution plume prediction supporting 6 aircraft and numerous universities, labs and institutions

NSF/NCAR C-130
NASA DC3
DOE B200
DOE G1
NASA J31
USFS Twin Otter





Balloon launches, surface supersites, mobile land-based observations.

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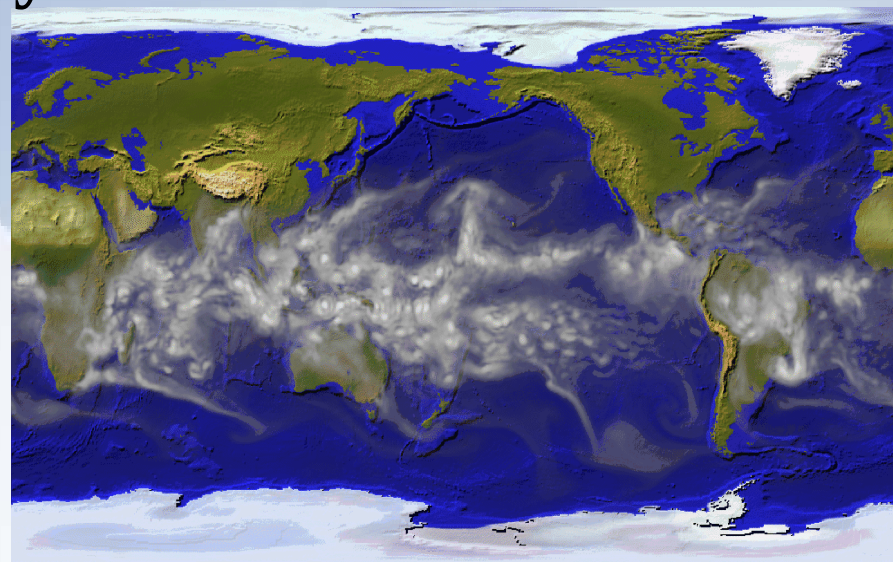
NCAR's Community Models

CCSM: Community Climate System Model



State-of-the-art Coupled Climate System Model

- Open Source Code and freely available data
- Significant development collaborations with:
  - 22 US universities
  - US Department of Energy (DOE)
    - LANL, LLNL, ORNL, ANL, LBL, NERSC
  - CRIEPI
  - National Air and Space Administration (NASA)

ARW: The Advanced Research WRF

Dynamics and Predictability of Weather Systems on Time Scales of 0-48h

- Over 3000 registered users make it the most used atmospheric model and provide an unprecedented pool of advanced research expertise;
- Operational use by the National Weather Service, US Navy, US Army, USAF, South Korean Meteorological Service, Indian Meteorological Department;
- Special forecasts are made by NCAR over the Antarctic in support of international operations there.